Hewlett Packard

The Spectrum Analyzer Project

In the late fall of 1959, after a week's vacation, I joined a Hewlett Packard project team that was working on the company's first venture into spectrum analysis. At Utah State, I had taken classes on electromagnetic theory, microwave devices, antennas, guided waves and transmission lines. I had also worked the Christmas holidays before on a project to measure the spectral characteristics of ionized patches in the upper air layers of the atmosphere.

I was excited to learn that the HP Microwave Lab was undertaking a project to design a Microwave Spectrum Analyzer. I was even more excited when the project manager, Art Fong, asked me to join the team. I promptly signed up and took all of the plans home to study and get up to speed on the project. I was assigned the microwave portion, probably based on my college emphasis. As the newest engineer on the project, I just focused on getting my part done and didn't try to add much to the other parts of the system. I continued in that mode for my first year on the project.

In the fall of 1960 I was approved by Hewlett Packard Management and Stanford University to enroll in the College of Engineering to pursue a Master's Degree in Electrical Engineering. I took two classes each quarter and finished the program in 1963. I was given time off to take classes but was expected to keep my part of the project on schedule, which I did. I took a broad range of classes primarily in communications and information theory. I enjoyed it very much and did quite well.

In 1961 and extending into 1962, I started taking a much more expansive view of my engineering responsibilities. Fortunately, my supervisor, Art Fong, was very encouraging of the engineers working for him to extend their thinking. Art was one of only two Chinese American Engineers at Hewlett Packard. He had graduated in Engineering from the University of California at Berkeley and then joined the Research Lab at MIT where much of the early work developing radar was done

The Spectum Analyzer Team
Standing left to right: Ed Phillips, Jerry Boortz, Ed Hurd, Bill Hanish, Rich Bauhause, Richard Anderson, Dave Veteran, John Cardin, Roger Rauskolb, MacMcGrath, Ron Given
Seated left to right: George Jung, Harley Halverson, Art Fong, Howard Poulter

during World War ll. Art was the natural choice to manage the spectrum analyzer project and most of the early design ideas were his and were very good.

After I had worked on the basic components for a little over a year, I saw a way to greatly increase the range of frequencies that the analyzer could present in a single display and to also greatly improve the speed with which a very large range of frequencies could be searched and analyzed. When I first presented my ideas to Art he said, "It sounds too good to be true." He then had me present it to the rest of the team and later to his manager. All were excited and said, "Let's go for it!" The project team worked hard to effect the necessary changes. The schedules were adjusted and the Hewlett Packard Spectrum Analyzer was on its way.

At that time Art added the system integration, performance testing and presentation analysis to my responsibilities. After a few months of hard work, the HP 851A/8551A Spectrum Analyzer was operational and ready for a limited showing in the spring of 1963. The special invited guests generally agreed that if we could meet the target specifications in production and make the whole instrument reliable that it would sell very well.

In the fall of 1963 we started showing it to a few potential customers. One of the first was the Army Fort Huachuca in Southern Arizona. Fort Huachuca was responsible for a great deal of Army research in communications, networking, radar and electronic countermeasures. Art Fong, a gentleman named Lyle Jevons and I made the trip. I presented the HP Spectrum Analyzer to a group of their technical people and demonstrated how it might help them better understand their research and design issues. After the presentation they asked how soon they could get one. Shortly thereafter we completed a pilot production run and began taking orders. I trained Lyle Jevons on the fine

HP Spectrum Analyzer - Block Diagram 4-18-61

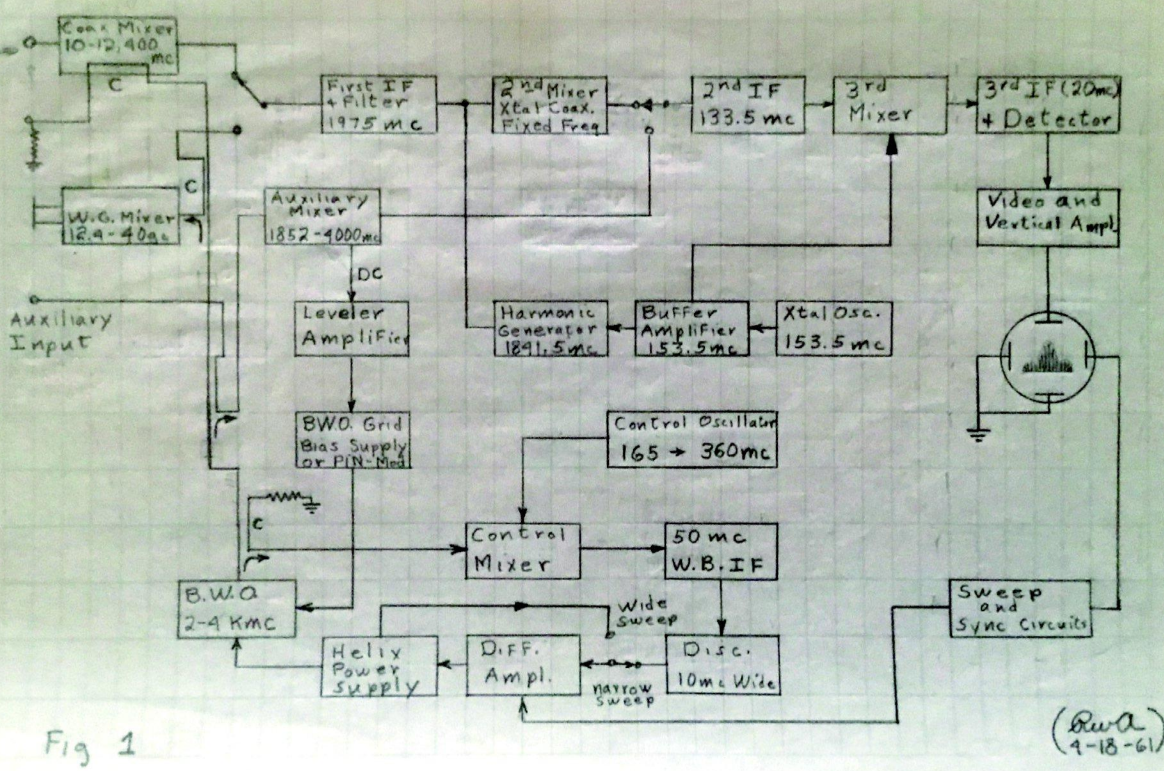
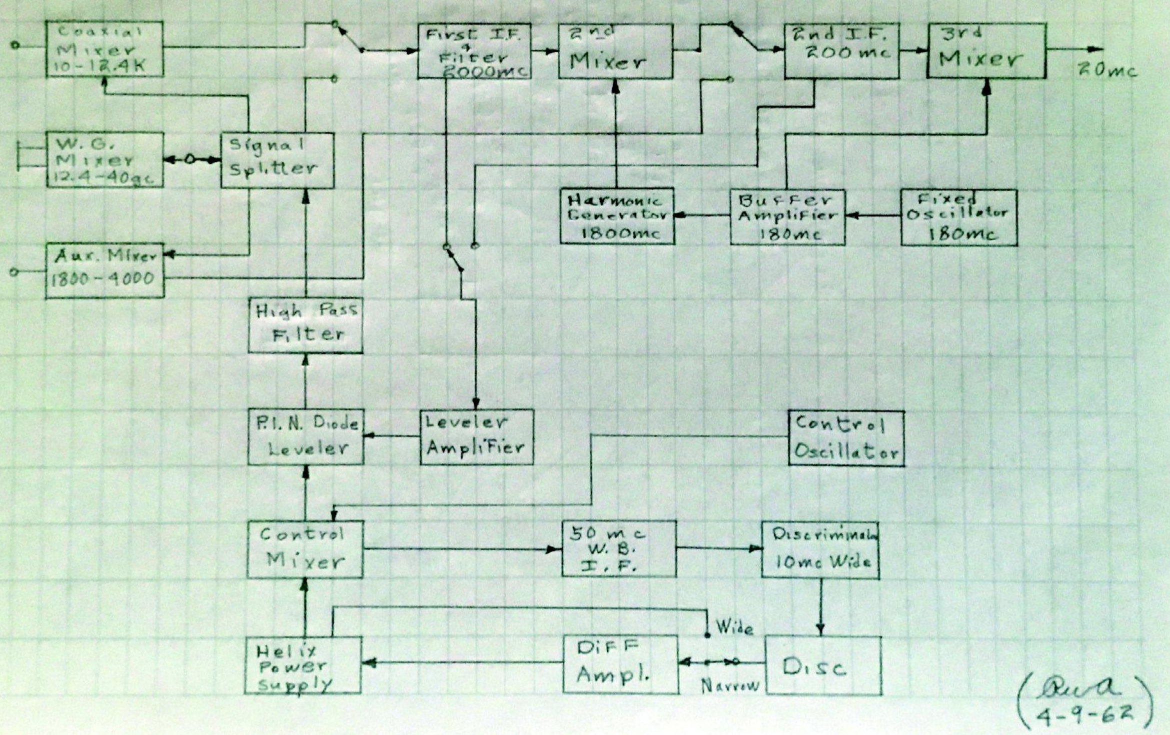


Fig 1

Spectrum Analyzer R.F. Section 4-9-62



The HP 851A/8551A Spectrum Analyzer

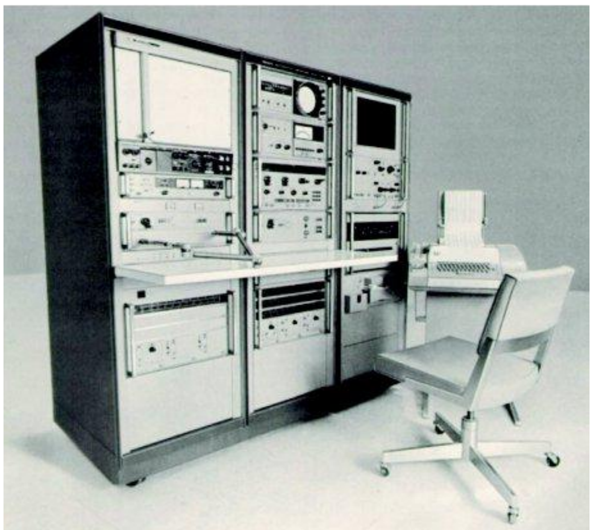
points of spectral analysis and he took one on a world introductory tour. Lyle traveled with it across the US and then to Europe over some six months. We could always tell where Lyle was by where orders were coming in from. The HP 851/8551A made a spectrum analyzer a 'must have' in every microwave and wireless engineering laboratory. HP quickly took about 90% of the market. It turned out to be HP's biggest revenue generator up to that point in time. I was also granted three key patents that helped HP retain a secure competitive position. A few of these original products are still in use after over 50 years since introduction. You might even be able to buy one on Ebay.

Looking for a New Challenge

With my first engineering project behind me and completion of my master's degree I was at a decision point. My advisor at Stanford told me I would be welcome to enter the Stanford PhD program. Since my work on the Spectrum Analyzer was over, the Lab Manager, Howard Poulter, assigned me to some research projects. One was joint with a part of HP called HP Associates (HPA) that was chartered to develop specialized semiconductor devices. In 1962 a British Physicist named Ian Gunn working at IBM's Watson Lab discovered that applying a sufficiently high voltage to a semiconductor diode could cause the diode to emit radiation in the microwave frequency range. Diodes constructed for this purpose were called Gunn Diodes and the oscillatory radiation was called the Gunn effect.

After Gunn reported his work, engineers at HPA were able to duplicate the Gunn effect and construct some experimental diodes. The problem was keeping the diodes from destructive burning under such high impinged voltage. I obtained some sample diodes and mounted them on coin silver posts in a coaxial structure. I was able to sustain oscillations continuously and may have been the first person to do so. The HPA lab director that I worked with was Mohamed M. Atalla, known as Martin or John Atalla. He had worked at Bell Labs where he co-invented MOSFETS. It was a fun assignment for me but we didn't think Gunn Diodes were ready for prime time

The Automatic Network Analyzer



The HP 8542A Automatic Network Analyzer
Hewlett Packard Journal, February 1970, page 3
Courtesy of the Hewlett Packard Company

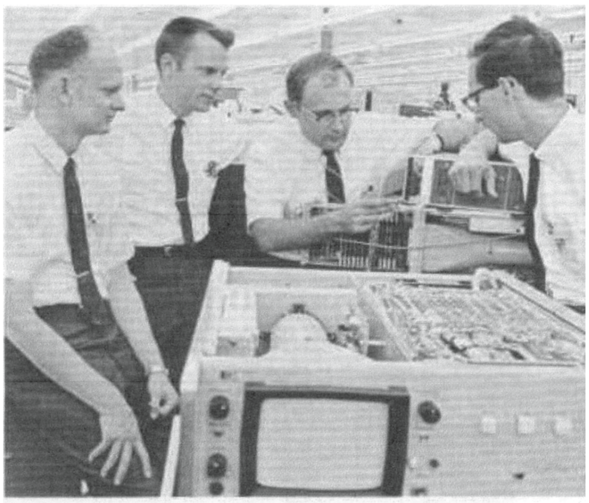
so I left the project to pursue other ideas.

It turns out that there were also some interesting new challenges to tackle in microwave and wireless engineering. I had some ideas that I developed in my spectrum analyzer work that could be coupled with developments at HPA and usefully applied in other areas. I collaborated with Paul Ely, who managed one section of our laboratory, on a technology investigation. Together we defined a preliminary block diagram for a wide band microwave network analyzer. Shortly after, Paul was appointed Microwave Division Engineering Manager replacing Howard Poulter. After a little courtship period, I decided not to return to Stanford and was asked, by Paul, to assemble the needed talent for a lab section to develop a microwave network analyzer. I was just 27 at the time and I think that made me the youngest engineering section manager in HP. That would have been in 1964, as I recall.

Engineering Management and Network Analyzers

Managing the Network Analyzer Section was really exciting for me. I had assembled a very talented, hard working team. I was also very much at home with the technologies and the intended applications that we were designing. I was given a free hand by division management to set the business strategy, define the products and guide the projects to completion. We were breaking new ground and were convinced that our solutions for network analysis and design would revolutionize the microwave and wireless industries. Hopefully just as much so as the HP Spectrum Analyzer had done. The big day came in late 1966 when the HP 8410A system was introduced in the marketplace. Over the Christmas holidays in 1966, I wrote a major technical paper on designing high frequency circuits using Scattering Parameters (S Parameters) which the Network Analyzer measured. The Network Analyzer and the S Parameter paper were both very popular and it was clear HP had another big winner in the Microwave and Wireless Space. The Microwave Division experienced another burst of strong growth. Because of the strength of the Spectrum and Network Analyzer program it was by far the largest division in the company. John Young was promoted from Microwave Division Manager to head a group of divisions under the title of Electronic Products Group. He was also elected to Vice President of Hewlett Packard Inc. In 1977 he would be elected President and CEO.

The Network Analyzer, like the Spectrum Analyzer, turned out to be an unqualified success. A highlight for me was traveling to Europe in the summer of 1967 to introduce the Network Analyzer there and train the sales people on the product. Moonyeen traveled with me. I did training in Edinburgh, Brussels, Frankfurt and Geneva. We also visited Southern Germany, Paris, Copenhagen, Ireland and Bergen, Norway.



Above all, Wescon is an arena of new electronic products. Just about every HP division will be represented at the Cow Palace with new instrumentation. Years of developmental work and months of special effort to meet the show deadline are involved. Such is definitely the case of Santa Clara Division's new 5480A signal averager which promises exciting new concepts, as in spectroscopy and bio-medical applications. The new instrument greatly enhances the resonance resolution of various other HP instruments. Reviewing format of 5480A exhibit are, from left, division engineering manager Dick Anderson, Skip Ross, Jim Daub, and Chuck Taubman.

Richard with three of the Division Engineering Team.

In Bergen we visited my grandmother's youngest sister Solveig. She showed us where my grandmother had been born and took us to church in the Bergen Ward. While we were in Brussels an enormous fire broke out in a large department store called L'innovation. It was across the street from the Metropole Hotel where we were staying. I was conducting a training session when someone looked out the window and exclaimed, "Oh my God!" The department store was about five floors of mezzanines and every floor was fully engulfed. I was gripped with fear because Moonyeen had planned to go shopping there that day. I hurried and called our room. I was relieved to hear her voice. Fortunately, we had been out late the night before and she had gone back to the room after breakfast for a nap which lasted until my call. When we were in Copenhagen, war broke out in the Middle East between Israel and some of the Arab States.

While we were in Europe, we left our four children with my parents. Debbie and Mike attended a couple of weeks at the Central School where I had received my first four years of elementary education.

As we were wrapping up work on the 8410A project I was surprised one day to get a call from David Packard, the Chairman and Co-founder of HP. At the time, HP was just completing the design of a digital computer, modeled the HP 2116A, in another division. He said, "Dick, I am going to send you a pilot production unit. I would like you to see what you can do with it."

I had only taken one three-hour college course on computers so it was all pretty new to me. But it started me thinking about how a computer like the 2116A might be coupled to an instrument like an 8410A to accomplish some really outstanding things. So I added one of my group of engineers, an engineer named Roger Raskolb, to my new little project and we let our imaginations run wild. We shared our ideas with others in the microwave lab including the lab manager, Paul Ely, who encouraged us to start a full project and he allocated us resources to make things happen. After a few days we had assembled enough pieces to start designing the software. Roger was pretty good at programming and I worked hard defining the procedures for calibration, measurement and analysis. Within a couple of months we had a very impressive set of results. With the computer tie in we could improve the accuracy of our measurements by as much as 100 times. We did this by measuring the repetitive system errors using very precise calibration standards, storing these in the computer's memory and then correcting for them in the data of the measurements of interest. The improvements and added capabilities were nothing short of spectacular. Needless to say, Dave Packard was very pleased and he quickly started bringing his industry friends over to see what we were doing. We defined a set of systems that we numbered and HP 854X Automatic Network Analyzers and HP had another set of capabilities in the rapidly expanding Microwave and Wireless Space.

Richard with Ed Hayes and Dave Packard at a Division Review, crica 1980.

microwave journal

HORIZON HOUSE 610 WASHINGTON STREET, DEDHAM, MASSACHUSETTS 02026

June 6, 1967

Mr. John Young
General Manager
Hewlett Packard
1501 Page Mill Road
Palo Alto, California 94303

Dear John:

The editors and staff of the Microwave Journal wish to congratulate Hewlett Packard on meriting the award for "Outstanding Microwave Product Development" of the 1967 IEEE Show.

The display of your "Network Analyzer using the Computer for time sharing techniques" has been selected as the "product of the show" at this year's exhibit. We are having a bronze plaque engraved for you, which you will receive within the next few weeks.

All of us at Horizon House extend our sincere and warm congratulations to you and your associates.

Sincerely,

Bill

William Bazzy

wb/sb
cc: Dean Abramson
GH&K

hh Offices: 500 5th Ave., Rm. 1602, New York, N. Y., 10036 ☐ 1-3 Charlotte St., London W.1., England

STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

DEPARTMENT OF ELECTRICAL ENGINEERING

January 7, 1969

Mr. William R. Hewlett
President
Hewlett-Packard Company
1501 Page Mill Road
Palo Alto, California 94304

Dear Bill:

This letter is to express the appreciation of the Department of Electrical Engineering at Stanford for the gift of four instruments which we received during the Fall Quarter from Hewlett-Packard. These included a network analyzer - 8410A, a harmonic frequency converter - 8411A, a phase-gain indicator - 8413A, and a polar display - 8414A. The financial value of the gift is significant - $6,135, but in addition the interactions with Dick Anderson of H-P have been interesting and valuable.

Last Spring one of the One-Year On-Campus students from the Bell Telephone Laboratories, Paul Smith, was interested in making measurements of transistors with a view to identifying some model parameters. As I had had an earlier contact with Dick Anderson on this same general subject, I called him and, as a result, Paul Smith had a number of visits at Hewlett-Packard where he measured the parameters of several devices. It was a very useful interchange.

My colleagues and I appreciate the gift of the instruments and also the usefulness of the technical contact which we continue to have.

Best regards.

Sincerely yours,

John

John G. Linvill
Department Chairman

JGL:jw
cc: Mr. R. Anderson ✓
Prof. J. B. Angell
Dean J. M. Pettit
General Secretary

COPY

Nov. 24, 1970 S. F. ADAM ET AL 3,543,197

RESISTIVE CARD HIGH FREQUENCY ATTENUATORS HAVING CAPACITIVE COMPENSATION

Filed Oct. 24, 1966

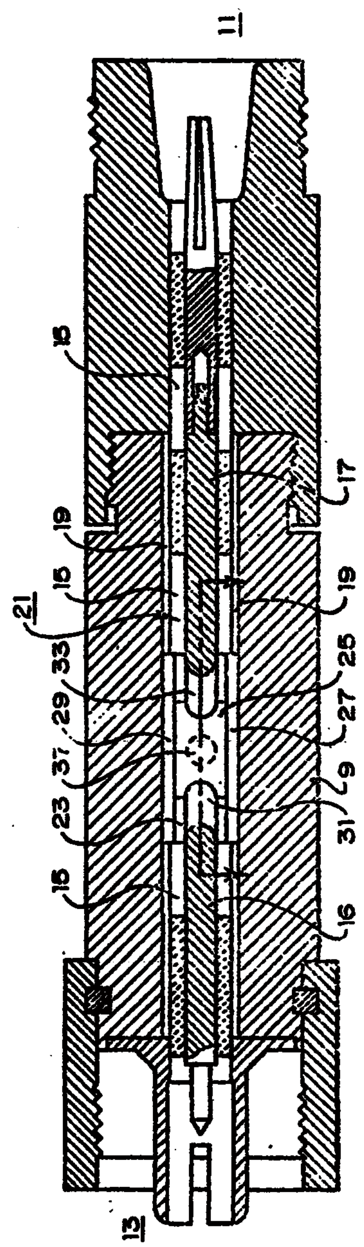


Figure 1

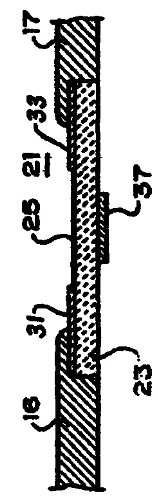


Figure 2

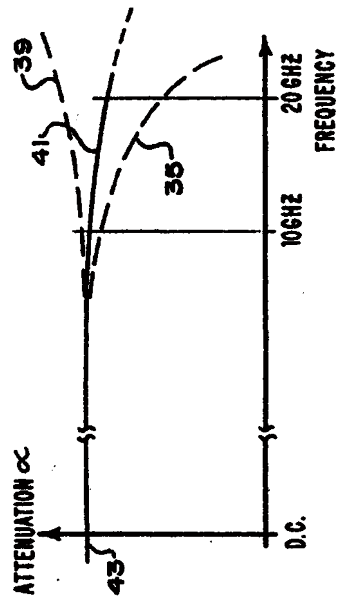


Figure 3

INVENTORS
STEPHEN F. ADAM
RICHARD W. ANDERSON

BY Q. C. Smith

ATTORNEY

May 17, 1966 R. W. ANDERSON 3,252,106

COAXIAL LINE PHASE DETECTOR FOR AUTOMATIC FREQUENCY CONTROL SYSTEM

Filed May 5, 1964

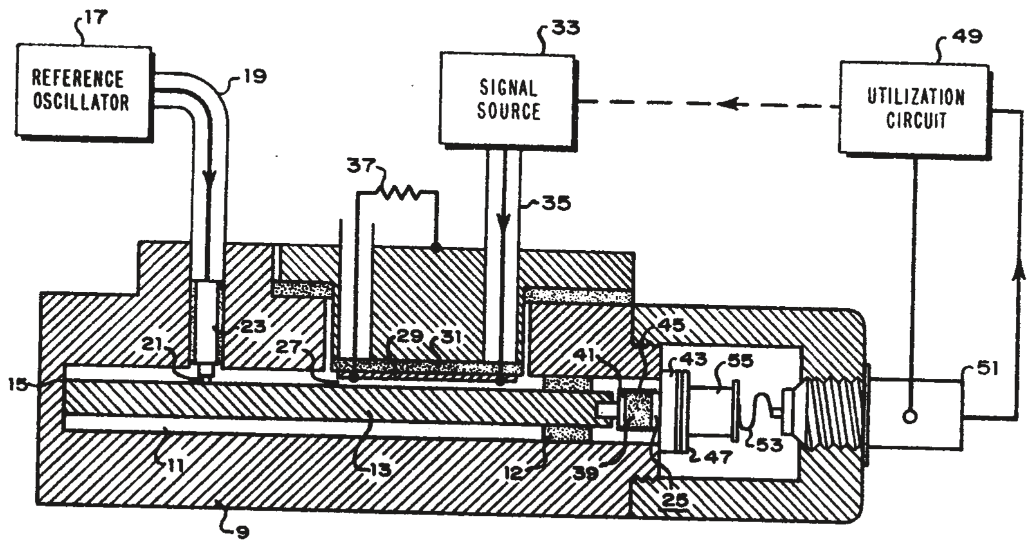


Figure 1

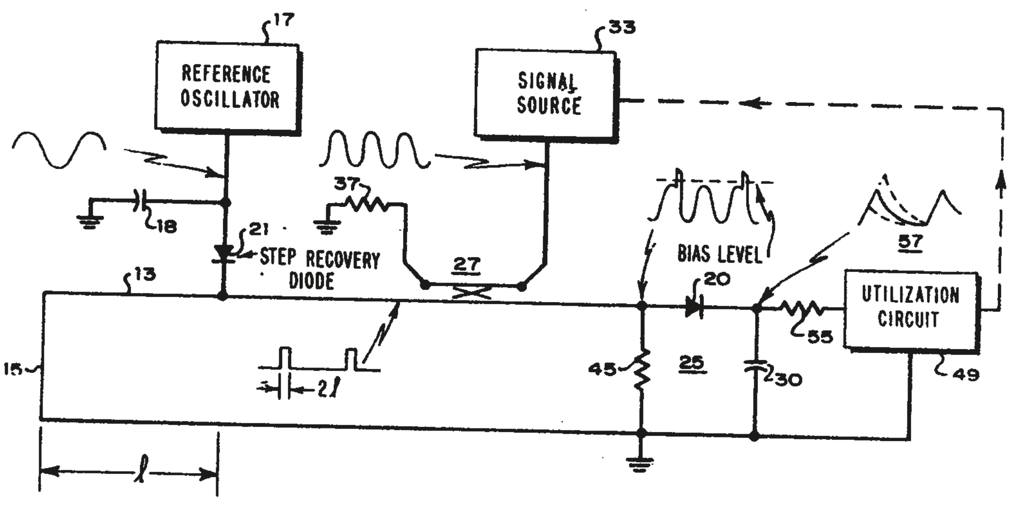


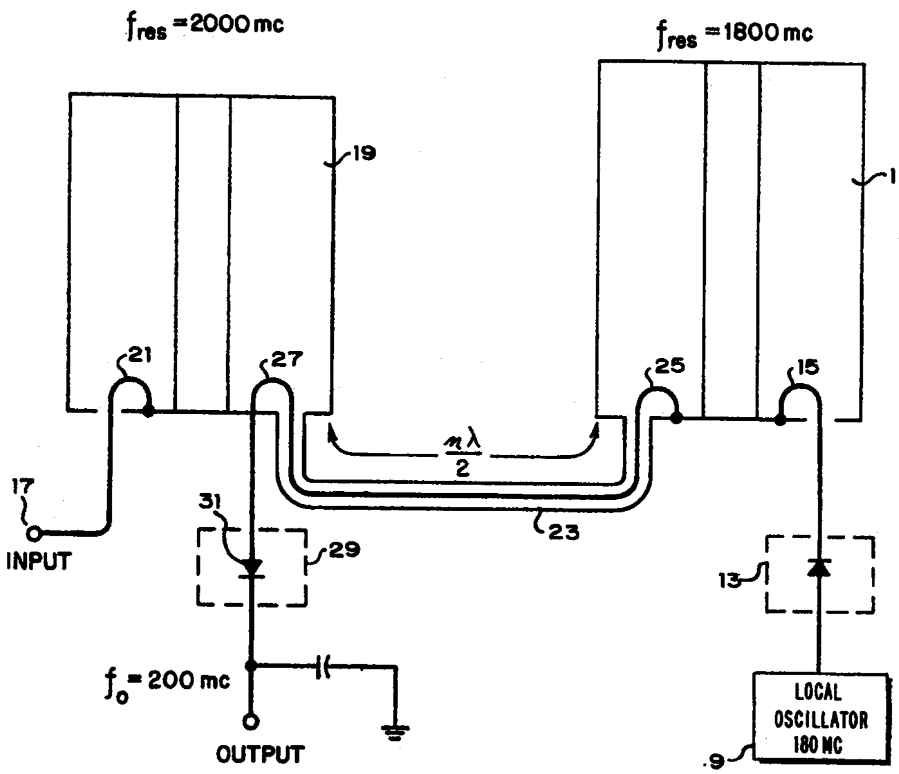
Figure 2

INVENTOR
RICHARD W. ANDERSON
BY A. C. Smith
ATTORNEY

March 21, 1967 R. W. ANDERSON 3,310,747

FREQUENCY CONVERTERS USING A TRANSMISSION LINE IMPEDANCE TRANSFORMER

Filed April 12, 1963

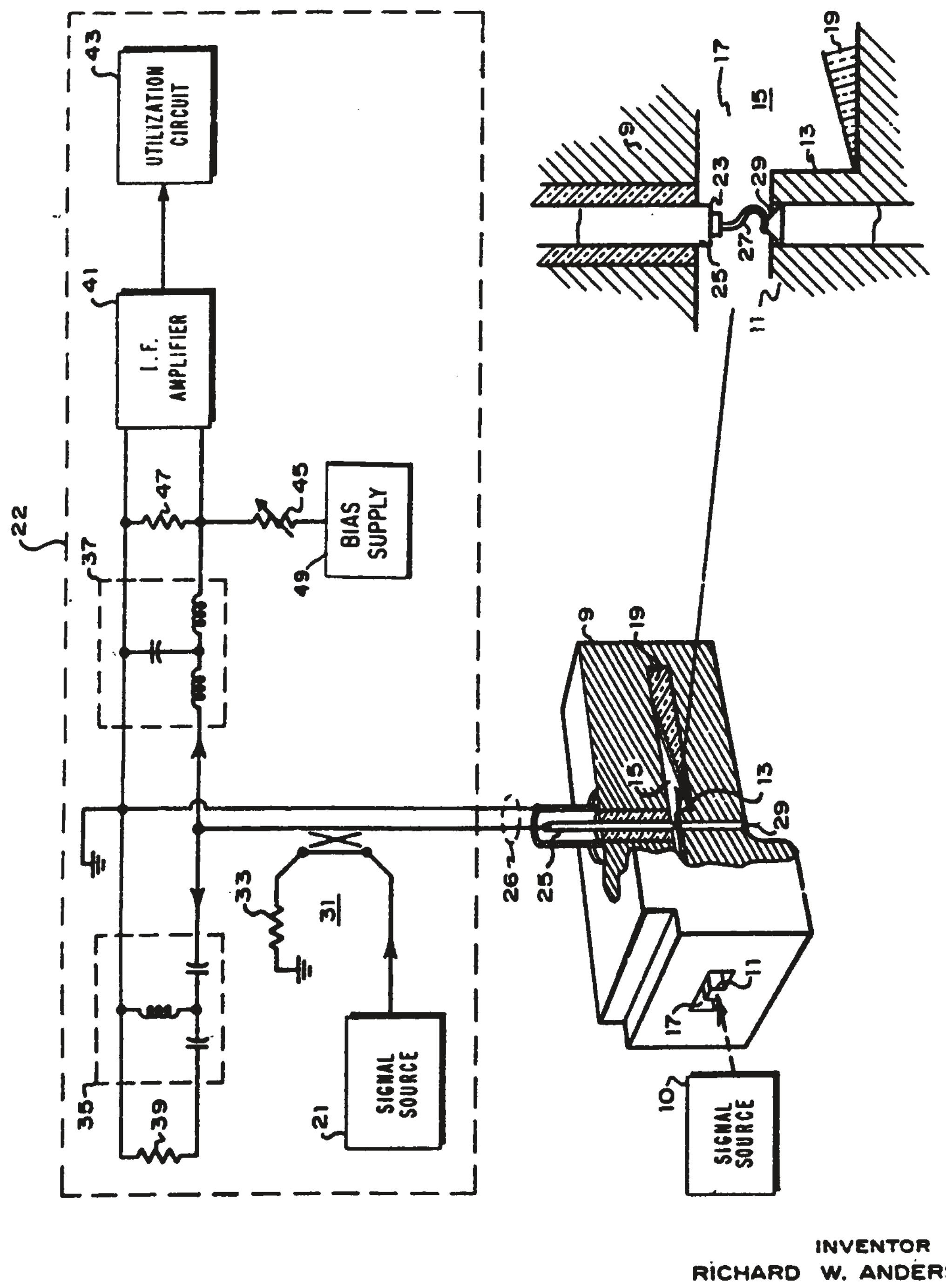


INVENTOR
RICHARD W. ANDERSON
BY J. C. Chapman
ATTORNEY

Sept. 5, 1967 R. W. ANDERSON 3,340,475

SIGNAL MIXER HAVING A COMMON INPUT AND OUTPUT PORT

Filed May 5, 1964



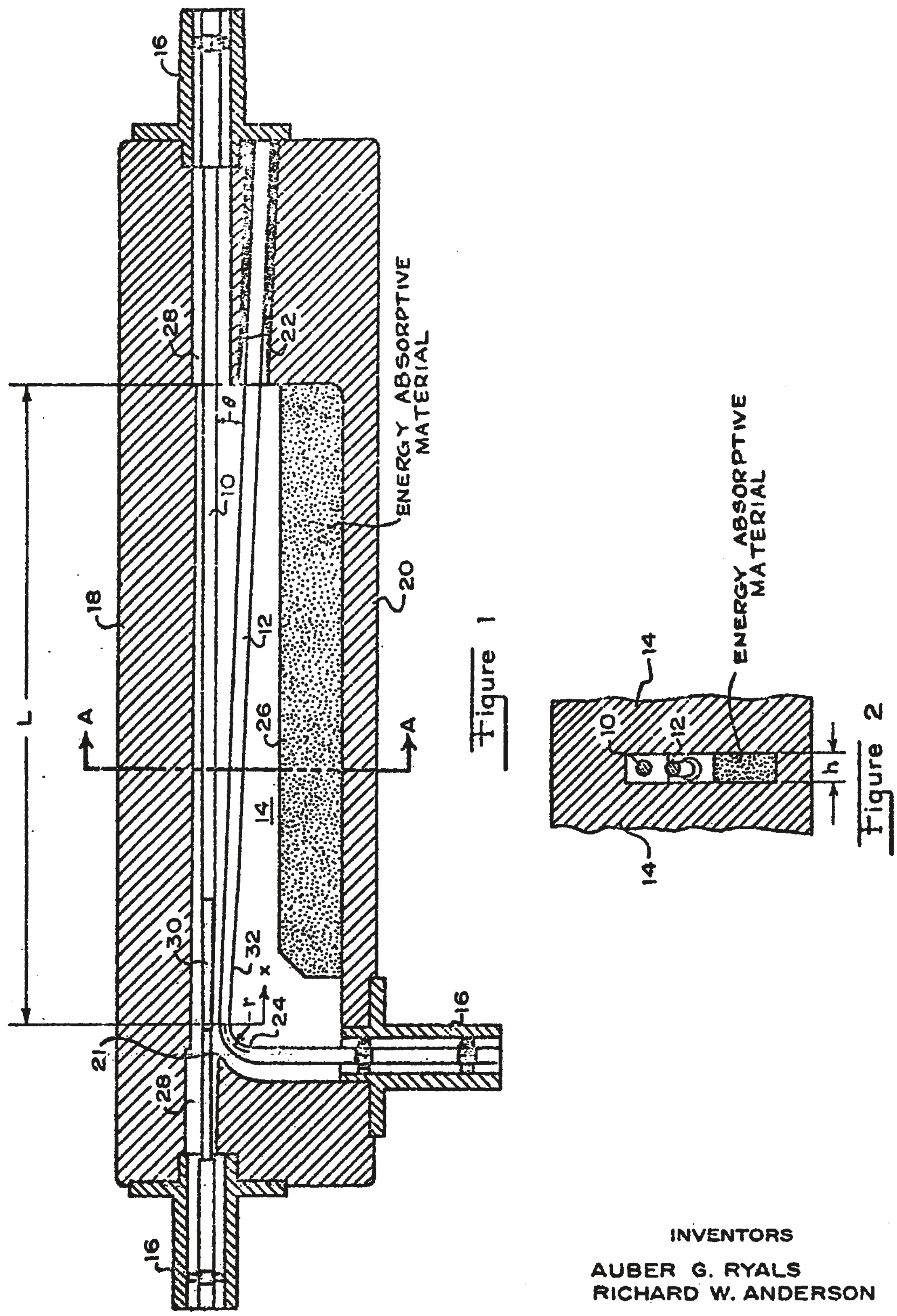
INVENTOR
RICHARD W. ANDERSON

BY Q. C. Smith
ATTORNEY

June 25, 1968 A. G. RYALS ET AL 3,390,356

TEM MODE COUPLER HAVING AN EXPONENTIALLY VARYING COEFFICIENT OF COUPLING

Filed July 30, 1965



INVENTORS
AUBER G. RYALS
RICHARD W. ANDERSON
BY

March 10, 1970 S. F. ADAM ET AL 3,500,263

PARALLEL-PLATE PERPENDICULAR STRIP CENTER CONDUCTOR TEM-MODE TRANSMISSION LINE APPARATUS

Filed Aug. 16, 1967 2 Sheets-Sheet 1

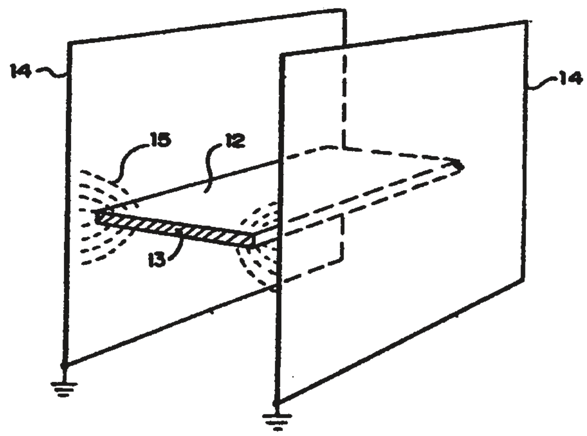


Figure 1

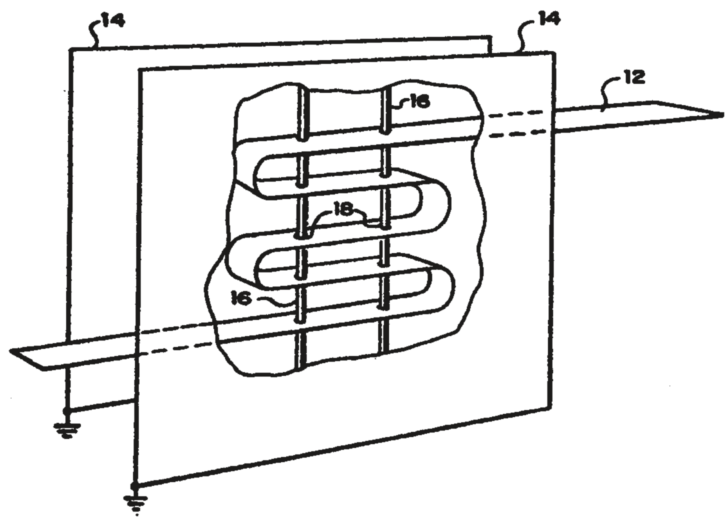


Figure 2

INVENTORS
STEPHEN F. ADAM
RICHARD W. ANDERSON
DAVID R. VETERAN

BY - Q. C. Smith

ATTORNEY

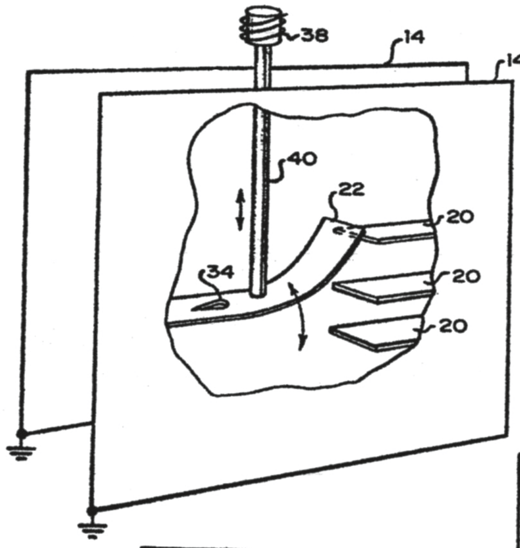


Figure 3

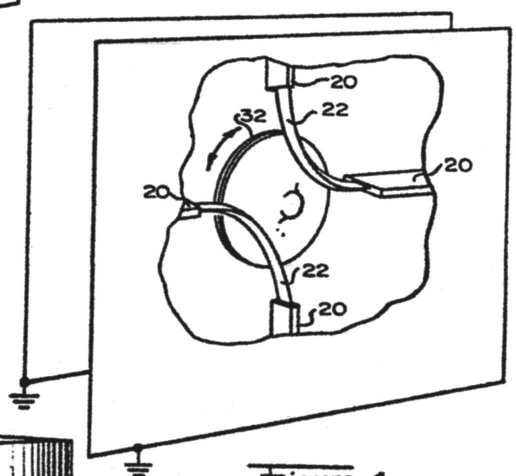


Figure 4

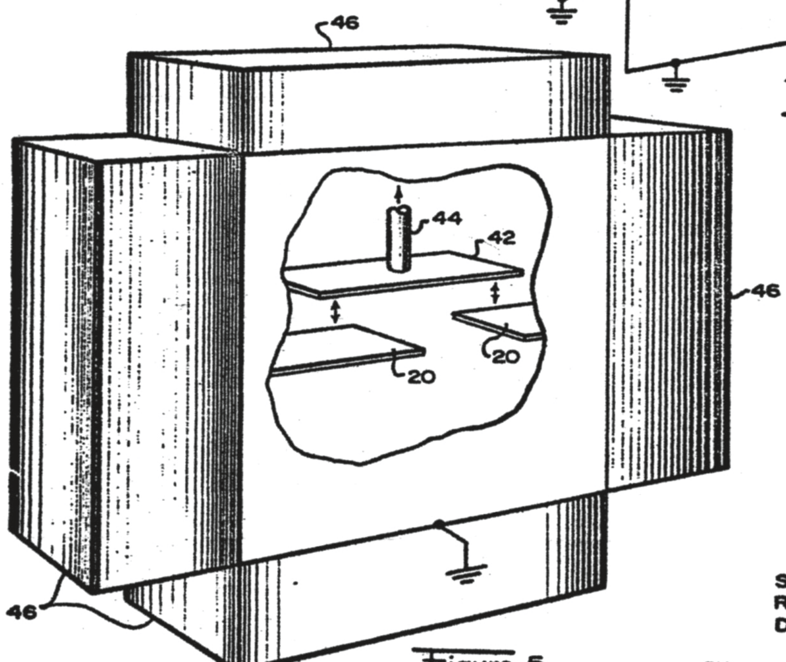


Figure 5

INVENTORS
STEPHEN F. ADAM
RICHARD W. ANDERSON
DAVID R. VETERAN
BY A. C. Smith
ATTORNEY

Counters to Computers

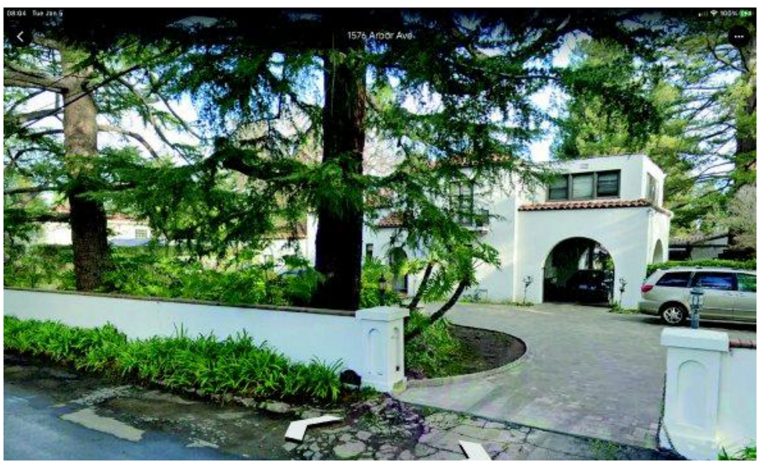
In 1968 I started to hear that I was being considered for the next level of responsibility, somewhere within the company. Some prospects were in the Bay Area where we lived, and others would require a move. Then one day I got a call from one Alan S. Bagley. He was in charge of a division called F&T for Frequency and Time. Al had led HP into its earliest work with digital technology, developing a line of frequency counters and precision clocks. Al was then both Division Manager and Engineering Manager. As might be expected that wasn't going too well. The division was a hodgepodge of projects, morale was low, and a lot of good talent was leaving. During the call, Al asked me if I would meet with him in his car to discuss his organization. I agreed to do so and we started a series of clandestine car rides for his purpose of interviewing me for the job of F&T Engineering Manager. He was nervous to give up the duties himself and he didn't want any of his division people to know he was talking to a 'Microwave Guy' as there was some division rivalry there.

I think he liked my leadership and technical skills but I also think he had some fear that at 31, I was too young to manage the F&T lab. Almost everyone there was older than me. I also think he was a little worried that I might try to get his job. After all, the former manager of the Microwave Division, John Young, was now his supervisor. I had no such interest. In 1969 we finally came to an agreement and I was appointed Engineering Manager of the Frequency and Time Division of Hewlett Packard. I believe that made me the youngest Engineering Manager in the Company.

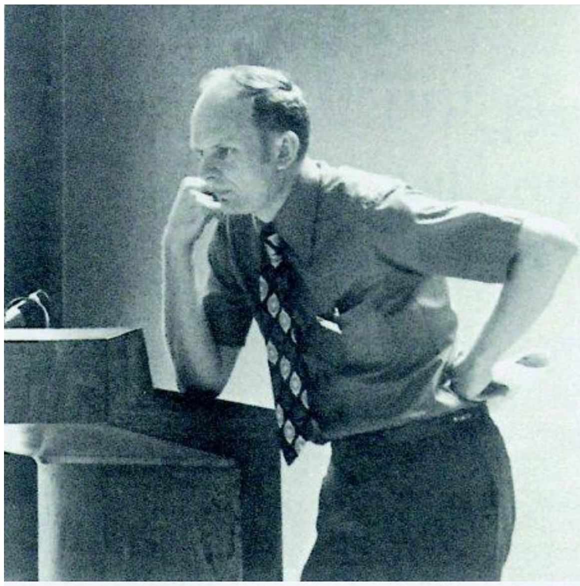
Since almost all of the people in the lab were new to me, I made a Herculean effort to know all of their names. They were impressed by that and I think most of the engineers really appreciated having someone in that job. I worked hard on two fronts: 1) Get a good idea of which individuals I could count on to produce, and 2) Evaluate how each project could fit into a workable strategy. Over the next few months I trimmed the Engineering headcount by about one third by removing the out of date, the lower skilled and the low enthusiasm engineers and managers. I also initiated an aggressive college recruiting program to add young, up-to-date engineers who hadn't learned that 'it can't be done'. I also pruned the project list to a workable number that fit some semblance of a business strategy and then staffed them to get the job done.

It is fortunate that I did this trimming when I did. In 1969 Richard Nixon became the US President. The Vietnam war finally came to a close and tensions eased a bit. With the close of the Vietnam period came big reductions in defense spending. Defense spending was a very big driver in the instrument business and we really felt it at HP. To make it even more difficult, Dave Packard joined the Nixon Administration as Undersecretary of Defense in charge of procurement. Dave was a wealthy man that had no interest in running for office and, believe me, he knew how to cut spending. By early 1970 the country was in a recession that hit technology particularly hard. By then, we had moved the F&T Division from Palo Alto to a new facility on Stevens Creek Blvd. in Santa Clara. That was very positive for division morale. The bulk of the division business was frequency counters and the business was becoming very competitive. We focused our efforts on two new families of very competitive, solid state frequency counters, digital signal processing with special computing algorithms (Fast Fourier Analyzer and Signal Averager) and digital circuit test. We got several solid new products to market which helped us weather the recession and set good growth opportunities for the future. Many of our designs incorporated custom integrated circuits. The Santa Clara Division included a complete integrated circuit facility with both bipolar and MOSFET capability. While I never designed an IC myself, many were designed by engineers who worked for me and I learned from them.

In 1970 we ran into a big family issue that was starting to overwhelm us. It is very hard to fit a family of two parents, three daughters and a son into a three bedroom, one bathroom home. We had been looking for a larger home in the immediate area but nothing had clicked. But early that spring the opportunity arrived. There was a very nice, large, Spanish style home on our same street about 300 yards from our home. We knew the family that lived there and we had told them how much we admired their home. It was an older home with two large bedrooms, two smaller bedrooms, three bathrooms, a large living room, a family room, a room we called the garden room, a partial basement, a small den and a dining room. It sat on a very nice half acre lot with an old two car garage behind. The owner called us one evening to tell us that he had accepted a job offer from the French Company, Schlumberger, and they would be moving to Paris. Would we like to buy their home? We shook hands after a house tour at a negotiated price of $65,000.



Our second Los Altos home, as it looked about 20 years after we moved. Image from Google Maps.



Accelerating growth of the instrument systems business was described by AMD's Dick Anderson. Points he raised included those of how to take greater advantage of computers and programmability.

Presentation to HP engineering managers. 1973.

It was a little scary with the recession but we moved in as soon as we could and put our present home up for sale. The recession of 1970 hit really hard so that we had to take every other Friday off without pay. The squeeze was on and it hurt. The hit movie that year was Butch Cassidy and the Sundance Kid. The movie theme song 'Raindrops Keep Falling on My Head' seemed very fitting. The home could sell today (2020) for as much as $5,000,000.00.

I enjoyed my time as Engineering Manager of the renamed Santa Clara Division but my time there was coming to an end. A new division had been organized as part of the Electronic Products Group reporting to John Young. It was called the Automatic Measurements Division or AMD. It was composed of parts of a couple of organizations interested in the 'Systems Business'. Several HP Managers had been tried in the leadership spot but none worked out very well. So comes a call from John Young: "Dick, how would you like to take the job of General Manager of the Automatic Measurements Division? I think you can do the job."

This was a harder decision than my last move. I wanted to talk it over with Moonyeen before I gave my answer. The managers that preceded me had crashed and burned. The risk was higher and there wasn't a high technology component that I could build on. But with Moonyeen's blessing, I accepted the position of Division General Manager of the Automatic Measurements Division. At 34, I think I was now the youngest Division Manager at Hewlett-Packard.

Bagley and Ely Compared

As I look back, I might have been the only person to work directly for both Paul Ely and Al Bagley. In retrospect, they were likely the two most obstreperous individuals in the company. Maybe the only other person to face dealing with those two was John Young. I will let John speak for himself, but as for me, I loved them both.

Instrument-based computer systems or computer-based instrument systems?

The Automatic Measurements Division already had established businesses. The first and oldest was Data Acquisition and Control. This was now mainly computer based systems with instrument front ends. The division had developed a computer operating system called RTE (Real Time Executive) to bring these two technologies together. The customers for real time systems like this were largely in manufacturing and mineral extraction. Such applications as oil well monitoring, engine testing and material stress testing were typical. The other business was Automatic Test based on computers and instruments combined to test complex electronic systems typical in military systems. Examples would include sophisticated aircraft, guided missiles and target-seeking torpedos. Another operating system called TODS (Test Oriented Disc System) had been developed for this side of the division. It was a tough management challenge to hold these pieces together and succeed in very different markets while supporting two separate sets of operating software. To make the job even tougher, the organization was spread over several small buildings in two different locations in Palo Alto. AMD employed about 1200 people.

After a few months a building became available in Sunnyvale, California about 15 miles south of Palo Alto. The building was large enough to bring the entire division together under one roof. It belonged to Fairchild Semiconductor, but they had closed their operations there so the building was empty. After a short visit Bill Hewlett agreed to have HP buy the building. We prepared the building for our use and moved the entire division there a few weeks later. In 1971 Dave Packard returned to HP and resumed his role as Chairman of the Board. He visited our division and took a big interest in what we were doing.

First Liftable Megabyte Computer from HP. 1974.

Over the next couple of years I had a lot of contact with Dave as he seemed to enjoy helping us sell our systems. He would call me and say, "I am going to visit my friend, the Chairman of XXX Company. Can you come with me and explain what you are doing in your shop?" I would go and it allowed me the opportunity to meet a lot of interesting people. He would run the meeting but would call on me to present our product and service offering. Among many others I presented to the top management teams at Firestone Tire, McDonnell Douglas and Boeing. We happened to be at McDonnell Douglas to see the first assembled F15 Eagle Air Superiority Fighter. While we were there Dave received a call from Secretary of Defense, Melvin Laird. Secretary Laird told Mr Packard that the US had just signed the Strategic Arms Limitation Treaty (SALT) with the Soviet Union. I learned the news before the press did. Packard also hosted the Chief of Naval Operations, Elmo (Bud) Zumwalt, at the company. Dave asked me to give him a tour of our operations before they went hunting on Dave's ranch on Mt. Hamilton. In February 1974 I spent a week in Russia where I was invited to deliver a lecture at the Lebedev Institute of High Energy Physics. The Lebedev Institute was where the Soviets developed nuclear weapons and nuclear power. Touchy visit!

About the time that I took the AMD job my former boss and good friend, Paul Ely, was appointed manager of the Data Systems Division which incorporated HP's computer programs. In 1974, Paul was put over all of HP's computer organization and promoted to Vice President. Paul then offered me the position of Division Manager of the Data

Systems Division in Cupertino. DSD was HP's biggest Division by then so it was a promotion and offered the opportunity to learn and participate in the computer business. I recall that the headcount was about 2500. So, l moved my office to Cupertino and waded full tilt into the world of computers. I held the position from 1974 to 1980. It was a genuinely fun time. I had a very good staff and had lots of interaction with our sales people and with customers. During my time there the division moved from almost break-even to a very profitable situation. During the time I was at DSD the computer business grew rapidly which created the need to create even more divisions.

Bad Accident

In 1979 I traveled through Europe with other computer business managers for the purpose of training and supporting the European sales team. I took my son, Mike, with me. It was right after he graduated from high school so it was kind of a celebration for him. We spent a few days in London and then went to Val d'Isere, France for some skiing with the European sales managers. After our stay there Mike flew home. Somehow he caught mononucleosis while he was there. He later developed a case shingles from it. Maybe too much fun in France.

After Mike went home, I flew to Oslo, Norway and then traveled by car to a ski resort area called Geilo. Again this was an opportunity to spend time with our best sales people from Northern Europe. While I was skiing an out-of-control skier from Sweden crashed into me, knocking me unconscious and causing bleeding from my head, nose and mouth. The ski patrol came and took me off the mountain by sled. An ambulance took me to the hospital in Honefoss where I spent a week in socialized medicine. When I arrived at the hospital there was no room for me so I had to be treated in a hallway. It turns out that I had a skull fracture that was causing swelling that gave me bad double vision. I also had two broken-off front teeth. Fortunately there was a good doctor there that had done some neurological training in the United States. He also spoke good English. He was able to help me get ready to return home as soon as my double vision went away.

An interesting thing happened once there was a room available for me. I was placed in a two-patient room with a Norwegian man a few years older than me. His wife would visit him every day and bring him some homemade treats. When she found that I was there, she kindly brought me treats as well. They spoke no English and I spoke no Norwegian so communication was only by smiles and nods. The mystery to me was, why was he there? I could see no evidence of any illness and he received no attention from any doctors or nurses.

On one of the days that I was there, a manager from our Oslo sales office came to visit me. He, of course, spoke Norwegian as well as English so I asked him if he could politely ask my roommate what he was hospitalized for. My friend found out that the man belonged to a very strong Union that entitled him to a medical rehabilitation on some regular basis and it was his turn. Just a nice, fully-paid rest and relaxation time in the local infirmary. But, there was no room for a guy with a skull fracture. We sure don't want to end up with a mess like that.

In 1980 I made a lateral move to a young, interesting division called General Systems Division. This division had the charter of building a business in general purpose business computers. This division produced the HP 3000 Computer System Family. It was a popular alternative to the IBM family of 'Mainframe Computers'. It was actually fun to compete with IBM. We felt like David dropping the giant Goliath. For me this was

Dick Anderson heads new Computer Systems Division

Dick Anderson, formerly general manager of Data Systems Division, has been named general manager of the Computer Systems Division, one of three new divisions created in August in the formation of the Business Computer Group under General Manager Ed McCracken.

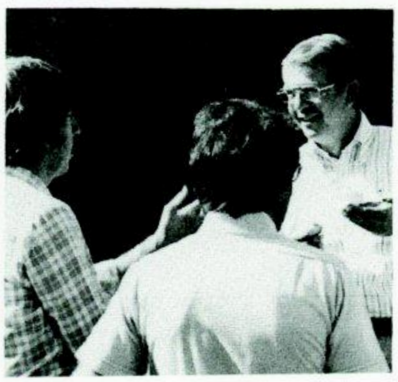
The Computer Systems Division now headed by Anderson has responsibility for the HP 3000 computer systems hardware and operating systems. He takes over from McCracken, who has been serving as interim general manager for the division in addition to his group role.

This is Anderson's third post as a division general manager since joining HP in 1959. He became general manager of the former Automatic Measurement Division in 1971, then was named to head the Data Systems Division in 1974. Previously he held key engineering positions as engineering manager of the Santa Clara Division and section manager in the Microwave Division. He holds a BSEE degree from Utah State University and an MSEE degree from Stanford University.

Functional managers under Anderson are Bob Frankenberg, hardware R&D manager; Howard Smith, software R&D manager; Jack Barbin, manufacturing manager; Bob Bond, marketing manager; Ken Coleman, personnel manager; John Corcoran, product assurance manager; and Alan Groves, controller.

All are from the original General Systems Division except for Frankenberg, who was formerly lab manager for DSD's High Performance Lab. Coleman, Corcoran, and Grove managed the corresponding functional departments at GSD, while Smith, Barbin, and Bond were on the management team for that division's HP 3000 program.

Dick Anderson



In a joint announcement made September 17, Group Managers McCracken and Chance detailed other changes within the Computer Groups organization: Gaylan Larson, formerly operations manager for the HP 1000 computer product line within DSD, was named to replace Anderson as general manager of that division; Roger Ueltzen, formerly marketing manager for DSD, was named to the newly created position of marketing manager for the Technical Computer Group; and the Roseville Operations, formerly part of DSD, has been established as an independent division, to be called the Roseville Division. It will continue to be managed by Alan L. Seely and is part of the Technical Computer Group, headed by Doug Chance.

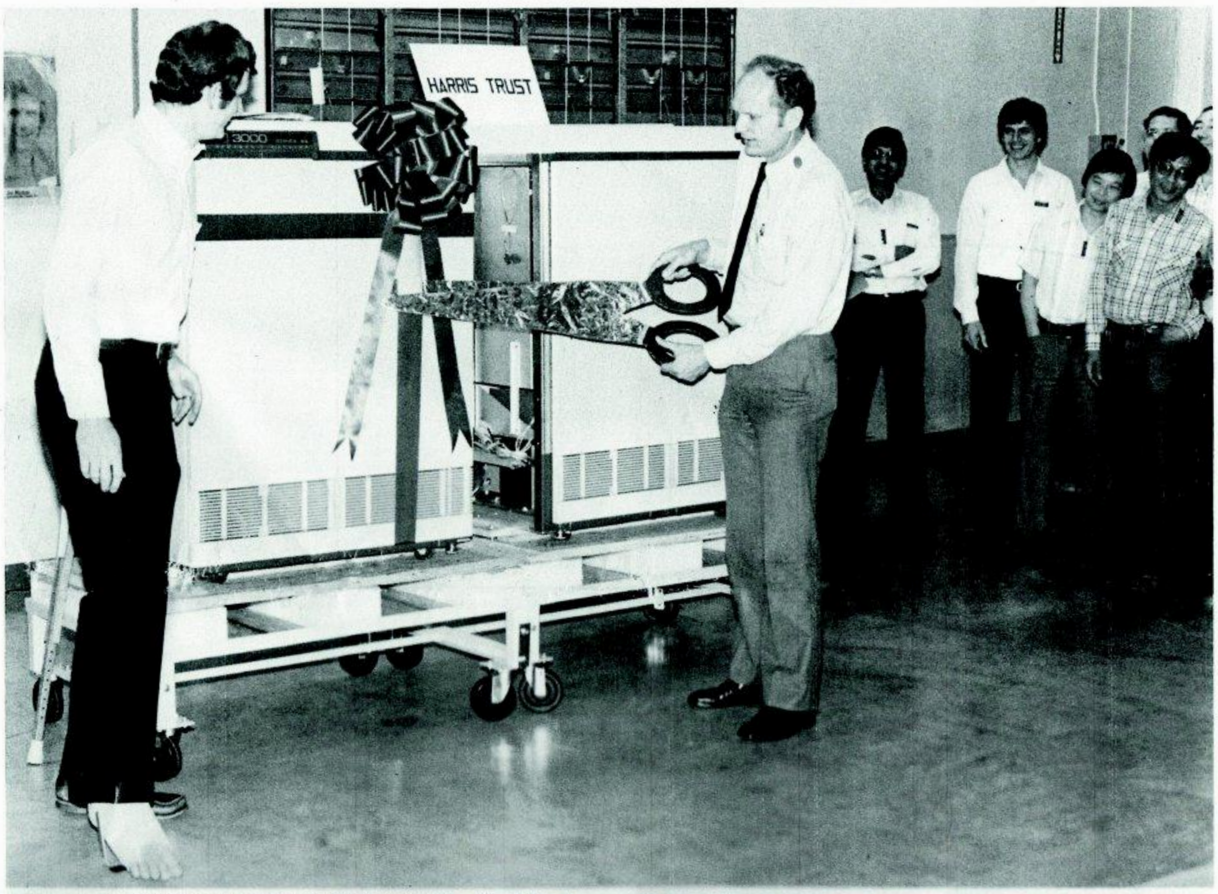
The McCracken-Chance announcement said the changes "are intended to solidify the management structure of the month-old Business Computer Group and to recognize continuing growth and achievement within the Technical Computer Group. These moves are evolutionary in nature – part of the continuing development of HP's computational products activities."

In addition to the Technical and Business Computer Groups, HP's Computer Groups organization includes the Computer Peripherals Group, the Data Terminals Division, and the Computer Marketing Group.

HP's First General Purpose Business Computer, the HP 3000.

Most Powerful HP 3000 System, circa 1983.

First HP 3000 Series 64 shipped by CSY



CSY's first Series 64 was shipped March 25 with appropriate festivities. Shown here at the ribbon-cutting ceremony are (from left) Rick Walleigh, Gemini production manager, CSY General Manager Dick Anderson, Manny Kohli, Mark Linsky, Danny Wong, Rich Kyu, and (behind Rich) Peter Rosenbladt. Trust Division of Harris Bank received first Series 64.

pretty much a management job. That being the case I focused most of my attention on two important management responsibilities: 1) quality of our products and services, and 2) people development, especially people that were historically under-represented in the best occupations. The division had a headcount of about 1500. My other major contribution was probably keeping a dedicated team happy and making a very good profit.

Quality Initiative

In the late seventies the advances in semiconductor technology coupled with demand for better and more information combined to boost demand for faster, cheaper and more powerful computers. Gordon Moore, a co-founder of Intel, formulated what became known as Moore's Law which observed that the semiconductor chips used in computers were advancing in price performance by 30% per year. That means each year 30% improvement in performance was available at the same cost or, conversely, the same performance could be achieved at 30% lower cost. The computer market exploded as computer makers poured out faster, cheaper and more useful computers at a breakneck pace. Computing functionality was also spreading like wildfire. These advances in technology were showing up in smarter cars, appliances, instruments, medical equipment, television sets, telephones, toys, automatic bank tellers and even shoes. The market was chaotic. Computation-based companies were springing up like tulips in spring and then dying out just as fast. But, in the chaos of the market dynamics, one important aspect was suffering—quality!

In 1980 when I was still general manager of DSD, we were in a very difficult battle to produce computers of acceptable quality. The semiconductor microchips were a particular problem. Manufacturers like Intel, Motorola and Mostek were moving manufacturing of chips to many different Asian countries in search of capacity and lower cost. I remember one of our suppliers' chips were having trouble with intermittent failures. In our effort to help solve the problem we opened several failed chip encapsulations. When we did we found that some of the chip capsules had tiny bits of contact wire rattling around inside. From time to time when the computer was moved, the wire piece would short out an internal contact and cause a miss-function. Since we couldn't open every chip to examine for this problem, we were forced to put each computer on a shake table to cause the failure in our place before we sent the problem to a customer. That is no way to run a computer factory. I might add that this is only one example. Quality needed to be addressed or this budding industry would be choked to death in the cradle.

We pushed very hard on quality for the remainder of my time at DSD. Our efforts were starting to attract some attention in the semiconductor trade press. In March, I was invited to speak on the subject of chip quality at a seminar held on March 25, 1980 in Washington, DC. Note from the program that the luncheon speaker was Illinois Senator Adlai E. Stevenson. He was the son of the Adlai E. Stevenson who ran for President of the United States in 1952 and 1956. It turned out that my talk was the only one that anyone would remember after the seminar ended.

The Bombshell

One of the seminar attendees was Ben Rosen, an electronics industry analyst that published a commentary newsletter called The Rosen Electronics Letter. Ben summarized my presentation, and provided comment that would put me at the center of the semiconductor and computer quality discussions. Follows photo static copies of news articles and the March 31, 1980 issue.

Tom Williams — Sunday Mercury News

Dick Anderson believes that American firms must build more quality into their semiconductor chips

Quality

H-P exec says 'usually reliable' semiconductors won't do

By Bruce Entin

Business Writer

During a busy day on the New York Stock Exchange last October, all trading was halted for about an hour.

Two months earlier on the West Coast, an Air California Boeing 737 nearly collided with three Air Force jets.

The two events were unrelated, but they were similar in at least one way: Both were caused by a breakdown in a computer.

Industry observers say computers — and the semiconductors that go into them — usually are highly reliable.

But critics such as Dick Anderson, an executive at Hewlett-Packard Co. of Palo Alto, says that usually reliable is not good enough for machines that have come to be used for diagnosing medical problems, running factories and controlling bank transactions.

Anderson feels so strongly about the subject that the soft spoken engineer publicly criticized American semiconductor makers last year for making sophisticated chips that did not pass inspection as often as the Japanese version. The chips which Anderson referred to are 16K RAMs (random access memory), which can store 16,000 bits of computer information on a piece of silicon smaller than a fingernail.

In Silicon Valley, it is an unwritten rule that you don't praise the Japanese too highly and you usually don't knock your peers publicly — even if they are competitors.

So why did an engineer go out on a limb? The answer is simple: He couldn't hold in his feelings any longer.

"I feel personally responsible for the performace of our products in hospitals and other places where loss of life and limb are important, or where the financial stakes are high," said Anderson, head of H-P's computer systems division.

The semiconductor industry, which makes high quality products 95 to 99 percent of the time, probably has a better record than most other industries, Anderson said. But numbers can be deceiving, he added.

The semiconductor industry is "playing a statistical game," Anderson complained in an interview. "Ninety-eight percent of the chips may be good, but the thing that worries me is the other 2 percent. To accept 2 percent of defects — to institutionlize it — is an error our society has made."

Anderson contends that U.S. firms do not build quality into the design of the semiconductors, mostly because it costs too much. However, U.S. firms waste more money by trying to rework chips that fail inspections after they come off the production line, he added.

There can also be a problem with a company's quality control.

Just last October, the semiconductor division of Fairchild Camera & Instrument Corp. of Mountain View said transistors it sold to the Pentagon for use in sophisticated military equipment may not meet the high requirements that the Pentagon demands.

This is because over a three-year period, Fairchild properly tested only a sampling of the devices rather than on all of them. Because these stress tests were not performed on all the parts, some may fail sooner than anticipated.

The semiconductor industry is not turning a deaf ear to the issue of quality. Partly as a result of Anderson's remarks, and partly because

Continued on Page 3C

A sustained drive for better quality!

Right: San Jose Mercury Tuesday, January 13, 1981

Below: San Jose Mercury October 22, 1980

Previous: San Jose Mercury January 11, 1981

Putting our chips on better quality

EVERYONE who makes a living in Santa Clara County can be grateful to Dick Anderson, the Hewlett-Packard engineer who made a public issue of semiconductor quality control.

Anderson made a couple of speeches pointing out that American-made silicon chips fail inspection more often than Japanese-made chips. He was talking specifically about 16K RAMs, random access memory chips that store 16,000 bits of computer information on a silicon chip smaller than a fingernail.

We wouldn't recognize a 16K RAM if it plopped off a Bayshore Freeway overpass, bounced on the windshield of our car and stared us smack in the face.

But we recognize that Anderson has a point. There is real concern about whether Japanese competition is threatening Silicon Valley in terms of quality control.

The quality control issue surfaced in different form recently when Fairchild of Mountain View confirmed that transistors it sold to the Pentagon for use in sophisticated military equipment might fail in greater numbers than was anticipated.

Business writer Bruce Entin wrote about all this in last Sunday's Mercury News, and he also reported that several Silicon Valley semiconductor companies are scrambling to make quality control a higher priority. Some say they started even before Anderson spoke out. And some are experimenting with their own versions of Japan's famous "quality circles," groups of employees who get personally involved, with management support, in finding new ways to do their jobs better.

According to Entin's report, there has been measurable progress in improving quality control of American semiconductors. And there also is evidence that the Japanese, meanwhile, are not only meeting some quality control standards, but exceeding them.

Obviously, the answer is not to try to hush this up, or to damn the Japanese, or to play like patriotism dictates an "America first" bravado while American products slowly and quietly slip into second place.

We've all seen what Japanese competition did to Detroit, and no one with an economic or personal interest in Silicon Valley wants to see it happen here. H-P's Anderson deserves credit for his warning that it could.

U.S. semiconductor firms boost quality, H-P exec says

By Bruce Entin
Staff Writer

A Hewlett-Packard Co. executive said Tuesday that the quality of certain memory chips made in the U.S. has improved by 50 percent since last year compared with their Japanese counterparts.

However, Richard W. Anderson, head of the computer systems division, warned that the Japanese are making strides in other areas that point to a "frightening scenario" for the U.S. semiconductor industry.

Last March, Anderson created a controversy in the semiconductor industry when he said that Japanese 16K random access memory (RAM) chips were superior in quality and competitive in price to their American counterparts. The 16K stores 16,000 bits of computer information.

H-P of Palo Alto had used Japan's memory chips in 1977 when U.S. suppliers were unable to meet the company's demand. Tests conducted by H-P engineers showed that Japanese memory chips had fewer inspection failures and breakdowns in equipment used by H-P customers, said Anderson.

When the supply of these chips became scarce again in 1979, H-P turned to the Japanese once more. And this time, the Japanese chips again proved superior in quality, said Anderson.

The Japanese now supply more than 50 percent of the memory chips used in H-P products, said Anderson.

Partly as a response to his speech earlier this year, semiconductor companies have improved the quality of their memory chips, he said.

In tests last year, "U.S. chips failed five to six times more often than Japanese memories," said Anderson. "But now, U.S. chips fail only two to three times as often."

Anderson criticized American management "mentality" that does not pay enough attention to quality.

"In the U.S., management assumes that problems will happen with the chips and they set up a testing system to deal with it," said Anderson. "But in Japan, quality is built into the chips so they don't need to rely on inspections."

Richard W. Anderson
. . . *New warning*

The Rosen Electronics Letter

80-5

March 31, 1980

● EIAJ Washington Meeting March 25 This session, sponsored by the Electronic Industries Association of Japan, was the bombshell. To date, most of the transpacific arguments have been put forth by adversaries espousing their respective positions: the Japanese manufacturers on one hand and the SIA members on the other. But the factor that was different in this Washington meeting, entitled "Quality Control -- Japan's Key to High Productivity," was the testimony of a disinterested party, a major U.S. semiconductor user with apparently no ax to grind. And to make his testimony even more valuable, he gave data -- hard data -- the first time we've seen numbers from other than an interested party.

The Anderson Bombshell

The morning in Washington began in rather ordinary fashion (read boring). Having awakened at 5:00 a.m. to catch a 7:00 a.m. shuttle to Washington, my reaction in listening to the initial speeches, one of which was in Japanese and the others of which were boilerplate from speakers representing Japanese semiconductor manufacturers, was muted at best. But then, after the coffee break, Richard W. Anderson, General Manager of the Data Systems Division of Hewlett-Packard, gave his interesting, provocative, and sure-to-spur-controversy speech.

Hewlett-Packard in general and Anderson in particular feel strongly about the quality issue -- hence Anderson's appearance before this group in which his motivation apparently was to raise quality control consciousness among his American vendors. As his example of relative quality, he used the 16K RAM -- the largest-dollar-volume semiconductor device in the world today. Starting in 1974 Hewlett-Packard bought all its 4K RAMs from U.S. vendors and apparently was planning to continue this policy with the successor 16K RAM. HP's first computer using 16K RAMs, announced in 1977, ran into a problem when HP's sole U.S. RAM vendor couldn't meet the demand because of yield problems. So, "after anguish," Hewlett-Packard talked to a Japanese vendor. HP was cautious because of its post-World War II impression of low Japanese quality, but the HP engineers put the Japanese 16K RAMs through a rigorous program. They qualified this Japanese vendor, and then began to buy more and more parts as the U.S. 16K RAM supply tightened.

According to Anderson, HP then started to notice something funny -- the Japanese parts were superior. They had fewer incoming inspection failures, fewer in the production cycle and fewer in customer hands. These qualities, in turn, led to lower systems costs and happier customers.

When the full-fledged 16K RAM crunch came in 1979, U.S. manufacturers began allocating parts among customers. HP again found itself in short supply and so it qualified two more Japanese suppliers to the Data Systems Division. And again, HP experienced the same phenomenon -- excellent quality at competitive prices.

Then, to buttress his qualitative remarks on quality with some quantitative information, Anderson provided the data shown in Table 1.

Table 1

HEWLETT-PACKARD TEST RESULTS OF 300,000 16K RAMs

Country	Vendor Identification	Incoming Inspection Failure Rate	Field Failure Rate (%/1000 hrs)	Quality Composite Index*
Japan	J1	0.00%	0.010%	89.9
	J2	0.00	0.019	87.2
	J3	0.00	0.012	87.2
U.S.	A1	0.19%	0.090%	86.1
	A2	0.11	0.059	63.3
	A3	0.19	0.267	48.1

**Figure of merit based on the two failure rates plus eight other parameters (cost, delivery, etc.) all equally weighted at 10 points.*

When the slide was projected on the screen, you could hear the audience's jaw drop as one. The data in the table -- for incoming inspection failure rates, field failure rates and a quality composite index -- represent tests on 300,000 16K RAMs, roughly evenly divided among three Japanese vendors and three American (none of whose identities was disclosed). He said that the data in the table is consistent with HP's experience since 1977.

What this experience suggests is that HP had zero incoming inspection failures in its sample from any of its three Japanese vendors as compared with American device incoming inspection failure rates ranging from 0.11% to 0.19% (roughly 50 to 100 bad devices per 50,000-lot samples).

More significant, in Anderson's opinion, and more damaging, were the data shown for field failure rates. The Japanese devices ranged from 0.010% failures per thousand hours for the best vendor to 0.019% for the worst. By contrast, the best

-5-

U.S. vendor had a field failure rate of 0.059% per thousand hours and the worst was 0.267% -- an astonishingly bad number. As he pointed out, the field failure ratio of the best Japanese vendor to the worst American was 27-to-1.

The final set of data showed a quality composite index, one which was made up of the sum of ten parameters weighted equally at 10 points each -- incoming inspection failure rate, field failure rate, cost, service, delivery and five other factors. Here, only one U.S. part was competitive with those of the three Japanese vendors on an overall basis and two were at significant disadvantages.

Anderson was careful to say that while the Japanese excelled at quality and were competitive in price, at no point was there unusually low pricing by the Japanese vendors. Indeed, he said that the Japanese vendors never have been the low bidder, though their prices were always "competitive."

Oh, the identity of the vendors. As we indicated, HP won't say (for obvious reasons). But, we believe the three Japanese vendors, in alphabetical order, and not necessarily in the order in Table 1, were Fujitsu, Hitachi and NEC. The three American vendors, in alphabetical order, and not necessarily in the order in Table 1, were probably Intel, Mostek and Texas Instruments.

MANAGING A DIVERSE WORKFORCE

The computer division general management assignments gave me the opportunity to work with many more women and minorities. Engineering had traditionally been a very white male oriented occupation. While I was in the instrument divisions there were a few Asian males joining the company but a dearth of Women, Blacks and Hispanics. Computers offered opportunity for change. The large part played by software along with financial, educational and business type applications made computer businesses much more attractive for job opportunities for women and minorities. In my time as General Manager of GSD I put together a staff consisting of three women, one black male and two white males.

In 1982 I was given the opportunity to take the summer off and go through the Stanford Executive Program (SEP). It was sort of a mini MBA for very experienced executives. The program was intended to train future CEOs. Sometime in late 1983 or early 1984 I was asked to be the Group General Manager of the Microwave and Communications Group. That was likely my best fit in the company and I accepted without hesitation.

SHARON HALL

Pat Castro (left), Irene Bever, Polly Johnson, Nancy Anderson and Mary Chin are among HP's growing number of women executives.

A woman's place: managing at HP

When Dick Anderson was general manager of the Computer Systems Division, women held half the spots on his six-person management team.

For Dick, now general manager of the Microwave and Communications Group, this seemed quite matter of course.

"I've thought a lot about the fact that when I was in high school, nine of the 10 outstanding graduates in my class were women and one was male (and it wasn't me). You have to ask yourself why not appoint a woman—just as you would a man—on the basis of ability, presence, leadership skills, intellectual capacity and personality: all the things that make a successful manager. I never had a qualm about the women I named to functional management positions, and the record shows I was right. As more and more women pursue technical careers, we'll see their rapid growth in companies. I hope HP will be a leader in welcoming them."

In the decades since equal opportunity legislation was passed in 1964, the numbers (see chart on page 5) show that the company has made a determined effort to recruit more women professionals. As more women enter the management pipeline, a small but growing number now hold executive-level positions at HP.

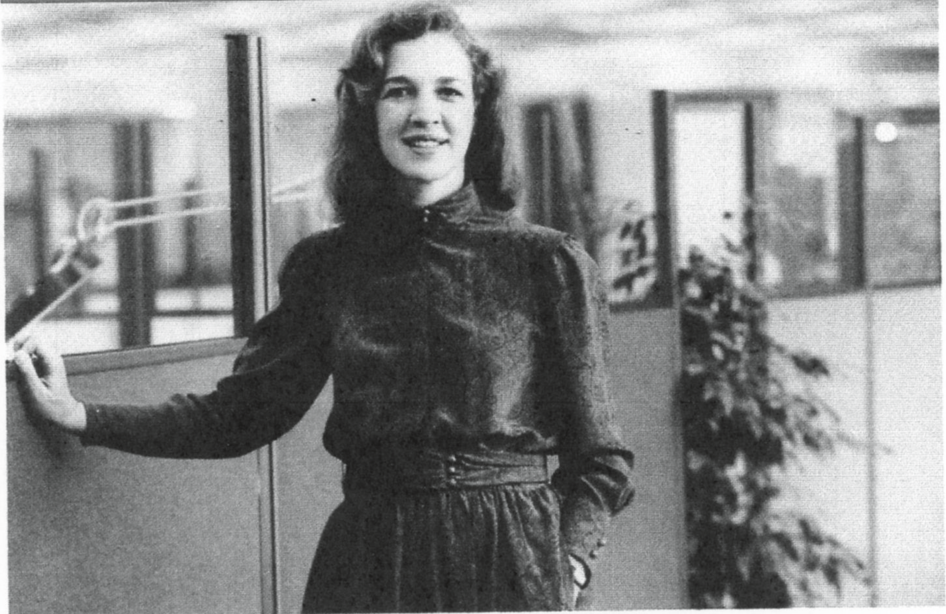
Top of the ladder

Some 50 women are currently ranked as functional managers or above, representing 5.6 percent of all top-level managers in the company worldwide and 6.2 percent in the U.S. (up from .5 percent in 1978). The first breakthrough in sizable numbers came in personnel. Today about half of HP's women executives head personnel departments. Recent months have brought a number of significant appointments such as the first woman operations manager, women R&D and manufacturing managers and the first woman area general manager in the field.

Even more women are knocking on that executive door. In the U.S., some 340 women make up 9.6 percent of middle-level managers. They are R&D project and section managers, product marketing managers, production and engineering managers, and district managers in the field.

They hold jobs in all functional areas, with many more in marketing (women make up 21 percent of all marketing middle-managers in divisions and in related jobs in the field) than in R&D (7 percent) and manufacturing (6 percent)—the three functional areas which have traditionally supplied HP's general managers. Women managers are 19 percent of the combined administration, finance and personnel middle-managers in the U.S.

One person who is frankly delighted to see women emerging into key roles is Pat Castro, director of the IC Processing Laboratory in HP Labs since 1979.



SHARON HALL

HP's first woman operations manager Laura Cory pauses on her way to a management meeting in Palo Alto. She heads the Semiconductor Productivity Network Operation.

She has been conspicuous as a highly-placed woman technical manager. "It's been no fun being the only lady at meetings," she says.

Pat believes in active guidance of women so they can know what skills they need to move upward in the organization and to deal with managers at higher levels. "But you can't choose your mentor," she warns. "Mentoring is never discussed but develops spontaneously." Given the present percentages of men to women managers, that coaching generally comes from a man.

When other women ask her for advice about getting into management, Pat suggests changing jobs "to learn new facets of the company." It's also wise to look for managers with different types of managerial strengths, such as giving good presentations, skillful negotiating and a clear understanding of the businesses HP is in.

Nancy Anderson, marketing manager for the Computer Systems Division, was one of Dick Anderson's appointees when he headed that division. (Quinn Cramer continues as personnel manager while Ilene Birkwood, who was quality manager, is now the director of software training for the company.) After getting degrees in math, she worked for two other companies before joining HP seven years ago.

"Because the computer industry is so young, it is very accepting of women," Nancy says. It is not unusual for customers visiting the Cupertino, California, site to hear women professionals give all the presentations on the

A TILT TO THE DISTAFF SIDE

HP's tilt toward computer systems and software—half of HP's design teams are working on software projects—will have an impact.

According to the National Center for Education Statistics, women earned 34 percent of bachelor's degrees in computer science in 1981-82 and 8 percent of the electrical engineering degrees with a computer-science component.

HP has been recruiting heavily in these fields, which accounted for 28 percent of its U.S. college hires in 1984, and is getting far more than its share of available women graduates. And HP is hiring women professionals across the board in increasing numbers—they made up 29 percent of all undergraduate college hires last year.

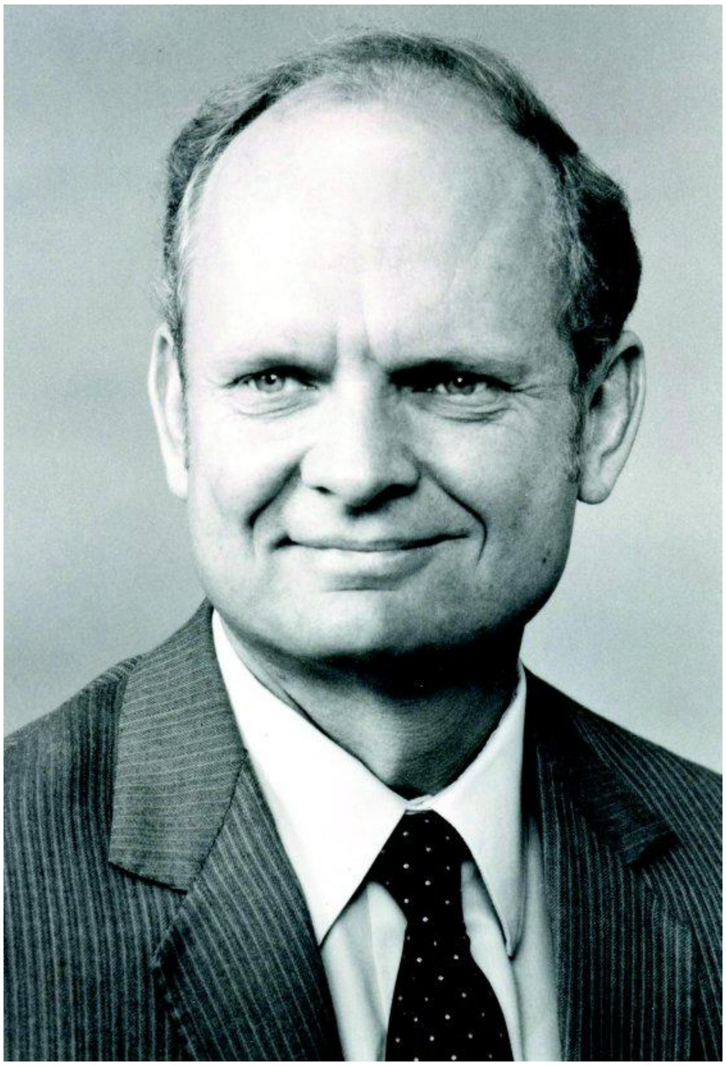
Women chemists, for instance, are well represented in the Analytical Group's division and field marketing. Ginny Curtis, a former college chemistry teacher who began selling for HP in 1983, topped all Analytical field reps in the world last year with $3 million in sales.

It's just a matter of time, assuming that these women stay with the company, that they'll be competing for managerial jobs in large numbers.

Back to the Future in Microwave & Communications

In late 1983 or early 1984, I accepted the position of Microwave and Communications Group (MCG) General Manager. Some of this was a return to my roots and felt very familiar. Other parts were new to me and provided the opportunity for personal and career growth. The annual revenue of the group was over one billion dollars and growing rapidly. These were the years of the Reagan economic boom. The two largest divisions were the Signal Analysis Division which had grown from the original Spectrum Analyzer entry and the Network Measurements Division from the Network Analyzer. It was gratifying to see how much these first two products had contributed to the success of Hewlett Packard. These two divisions, together with an important technology center, were based in Santa Rosa, California. The other divisions derived from the former Microwave Division were the Spokane Division in Spokane Washington and the Stanford Park Division in Palo Alto. There was also a metals and plastic based fabrication center in Palo Alto. Over the years the group had also incorporated three additional divisions, the Colorado Telecommunications Division in Colorado Springs, the Queensferry Telecommunications Division in South Queensferry Scotland and the Kobe Instrument Division in Kobe, Japan. The group headcount peaked at over 10,000 people. It was a great opportunity for me, and in 1986, I was elected a Vice President of the Hewlett Packard Company along with my continuing responsibilities as General Manager of the Microwave and Communications Group.

The traditional microwave instrument business had been driven by military spending which peaked in the Reagan years. By 1986 it was clear that the defense growth driver would not continue and we needed to pursue opportunities in the rapid growth areas in all types of communications. In the coming years we investigated opportunities in cellular communications, satellite communications, packet switching networks, network television, global positioning networks, fiber optic communications, surveillance systems, wireless interconnection, classical telephony and too



Hewlett Packard Vice President. About 1980.

many more to list here. We also took initiatives in computer aided design, comprehensive test systems and network management.

As we searched for opportunities one thing seemed clear, it would take more than one new initiative to keep the business healthy and growing. We were unlikely to find another giant opportunity like Spectrum or Network Analyzers. To help our efforts we made a few strategic acquisitions. We acquired a protocol testing company in Edmonton, Canada; a telecom test joint venture in Padua, Italy; a microwave computer aided design (CAD) company in Northridge, California and entered into some joint venture projects in China, South Korea and Europe. To build on our historic strengths and success, we initiated new business directions in:

1. Wireless Transceiver (cell phone) Test
2. Fiber Optic Test
3. Microwave Computer Aided Design (CAD) Solutions
4. Microwave Test and Measurement Systems
5. Integrated Network Test and Management
6. Video System Test and Management

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ROBERT K. JAEDICKE
ENDOWED PROFESSOR AND DEAN
GRADUATE SCHOOL OF BUSINESS

September 25, 1985

Mr. Richard W. Anderson
Manager, Microwave and Communications
Group
Hewlett-Packard Company
3000 Hanover Street
Palo Alto, California 94304

Dear Dick:

"Who's News" was more interesting than usual. Congratulations on your new position as Vice President. I send you greetings and best wishes for every success from your GSB friends.

Best personal regards.

Sincerely,

Bob

Robert K. Jaedicke

RKJ:emd

VOL. 26, NO. 3 • MARCH 1987

Microwaves & RF

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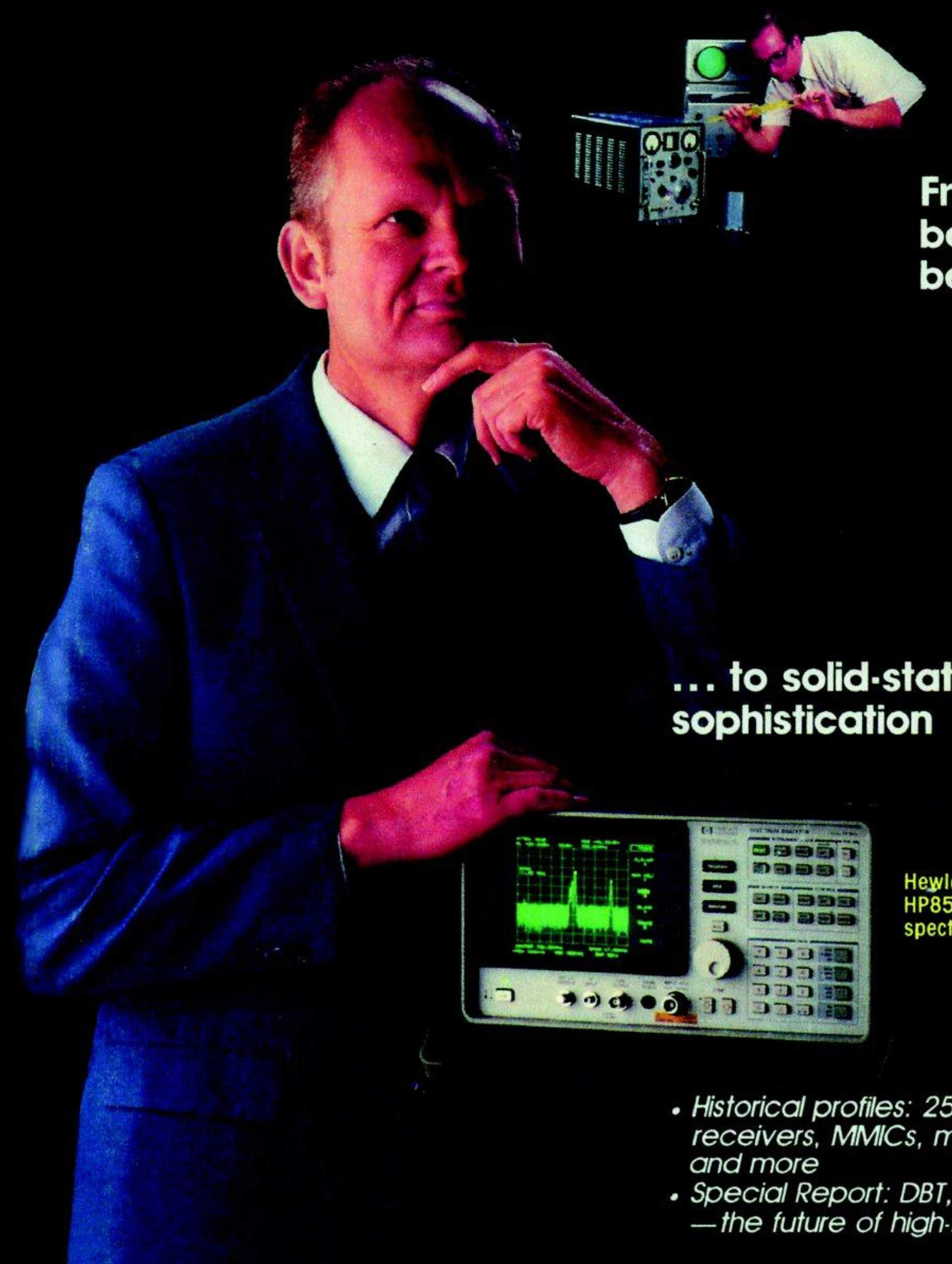

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FEATURES

New riches from superconductors

NEW YORK: A revolution in the field of superconductivity promises new riches for companies able to adapt the new technology to high-performance computers, medical devices, "flying trains" and nuclear fusion.

US companies are ahead in the search for new applications, but they are looking over their shoulders at Japan. Americans fear they could lose their edge in superconductors the same way it was left well behind in such technologies as the transistor and the integrated circuit.

"It (superconductivity) will be a very good litmus test of seeing which companies or countries can keep marching ahead," Mr Praveen Chaudhari, vice president for science at International Business Machines Corp, said in a recent interview.

"We're very sensitised to this issue in the United States," Mr Chaudhari said. "This is something we all ought to watch very carefully."

Superconductors are little-understood materials that lose all resistance to electricity below a certain temperature. The threshold used to be not far above absolute zero, which is a frigid 459 degrees below zero Fahrenheit (-359C).

Starting with a discovery last year by IBM scientists in Zurich, Switzerland, and accelerating this February, scientists around the world have been leapfrogging each other in raising the threshold temperature to levels that open new worlds of commercial possibilities.

Theoretically, with better superconductors, computers the size of a bread box could run at super speed without overheating; bullet trains could float on magnetic fields; cheap, clean and abundant energy could be created through nuclear fusion.

The commercial market for products using superconducting elements could range from US$11 billion to $36 billion a year by the year 2000, according to an article in Naval Research Reviews that was published in 1985, before the latest breakthroughs.

Superconductivity is still in its infancy, that tender age when corporate researchers still divulge their results at packed scientific meetings instead of hoarding potentially profitable findings.

In fact, some scientists say it is too soon to start developing products for sale because the state of the art is advancing so quickly that any device is likely to be out of date by the time it reaches the market.

Financial analysts say sizeable profits from superconductivity lie well into the 1990s or beyond.

"Speculation is moving light years ahead of the reality. I just don't see any impact right now," said Mr H P Smith, an electrical industry analyst for Smith Barney, Harris Upham and Co.

Nevertheless, dozens of companies in the United States are throwing money and people into the race.

"I can't imagine a major institution in this country that doesn't have a serious effort in this area," said Mr Robert Dynes, director of chemical physics research at A T and T Bell Laboratories in Murray Hill, New Jersey.

The Japanese government, following a proven formula, is planning a coordinated effort of corporations, universities and government labs.

"It seems like superconductivity is another thing they have targetted almost as a national focus," said Mr Thomas Chesser, a Japan watcher for Smith Barney.

Research is already under way at Hitachi Ltd, NEC Corp, Mitsubishi Electric Corp and other corporations as well as the University of Tokyo and labs run by the Ministry of International Trade and Industry, among other places.

The Japanese government's spending on superconductivity research is likely to increase tenfold this year, predicted Mr Kiichiro Yamagishi, past director of technology for the Japanese External Trade Organisation in New York.

He said he could not provide figures.

"In the past, Japanese companies were very skilful to commercialise new technologies, very quick," Mr Yamagishi said.

But Mr Yamagishi said it is too early to concentrate on commercialisation.

Scientists in the United States, Japan and elsewhere should share their findings for their mutual benefit, he said.

The United States is No 1, or at least tied for the lead in superconductivity research at this point, several scientists agreed.

Many companies — Hitachi, A T and T, IBM and General Electric Co, for example — long ago developed detailed plans for superconductors that they had to shelve because the economics weren't right with the old materials.

Those plans are being dusted off. But the biggest profits might come from products that have not even been dreamed of yet, Mr Chaudhari and others said.

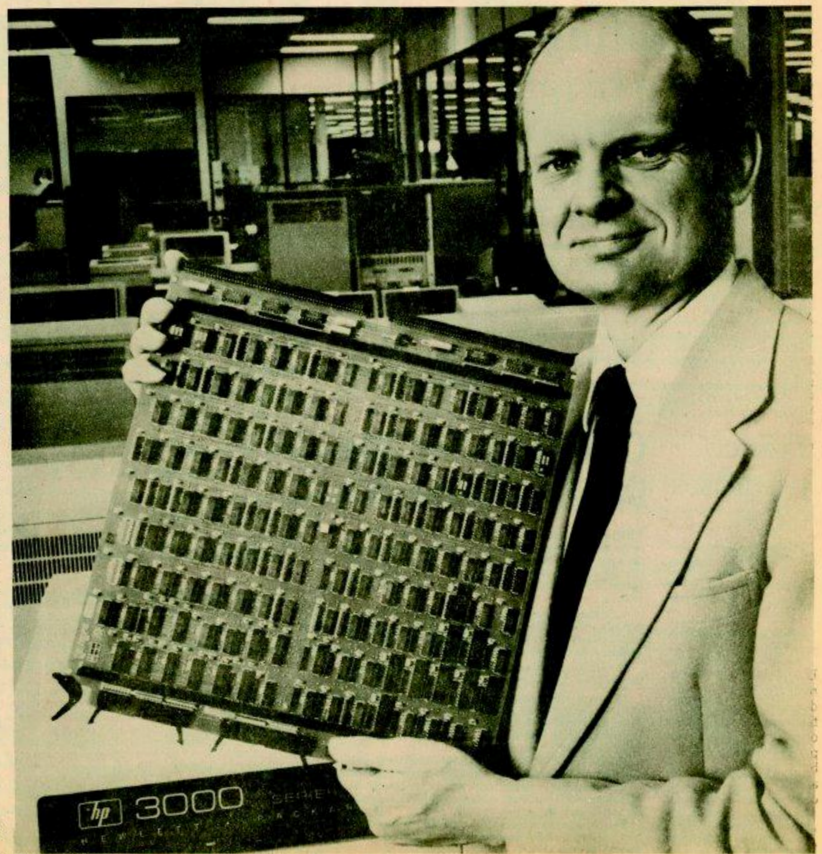
"At this point we're definitely keeping an open mind," said Mr Michael Jefferies, manager of GE's research and development center in Schenectady, New York.

Varian Associates Inc of Palo Alto, California, hopes to become an early winner from superconductivity by selling equipment to other researchers.

Varian is modifying a chip-making machine so it can lay down superconducting materials on chips one molecule at a time.

Far larger companies — including the Japanese — are working on similar machines.

But Varian is counting on its expertise and its links with scientists from neighbouring Stanford University to come out ahead. — AP



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安德森（台揚董事）：

台揚有能力與世界大廠結盟

產品集中火力 客戶導向 人才優秀造就轉型成功

（記者詹惠珠／台北）

台揚科技公司股價在五個月內大漲四倍，外資持有台揚的股票從1,500張大幅增加到48,000張，台揚股價飆漲，反映台揚成功的轉型，而主導台揚轉型的安德森（Richard WatkinsAnderson，台揚公司提供）昨（28）日指出，在無線通訊時代來臨，全世界沒有一家公司像台揚的產品有多元化的組合，台揚有能力與世界級大廠進行策略聯盟，台揚的股價未來表現會比其他通訊股更好。

安德森是美國惠普公司前任副總裁，1992年至1997年是以美國惠普公司的法人代表，擔任台揚的董事，1997年擔任台揚的執行總裁（CEO），主導台揚的改造，將十餘種產品縮減為四種，使台揚不但轉虧為盈，更成為通訊產業的明日之星，安德森為現任台揚董事，他強調，台揚的轉型成功來自產品集中火力、客戶導向、以及優秀的人才三大因素，以下是訪談紀要：

問：通訊時代來臨，台揚在國際市場的競爭力和發展利基為何？

答：台揚未來的發展潛力是無限（unlimited），其商機來自無線通訊、網際網路、手機上網、寬頻等，市場的需求相當大，而歐美等通訊大廠會釋出更多的委外訂單（outsourcing），而全球沒有一家公司像台揚具有相當獨特的利基，包括技術、研發、製造、產品領域的多元化，加上台揚所生產的產品進入障礙相當高，台揚在國際上的地位可以說是second to none。

過去當我與世界級的大廠如朗訊、

Netro介紹台揚時，他們都樂於與台揚接洽，台揚也有能力與世界級的大廠進行策略聯盟，台揚已不是去「尋找」機會，而是從機會中去「篩選」合作夥伴的名單。

問：你是否可以談談台揚的轉型和台揚未來的發展？

答：三年前台揚的產品線相當多，並沒有集中火力，在看好無線通訊的市場，台揚進行組織重整，這是台揚轉型成功的關鍵因素；另一個則是並以客戶導向，生產線配合客戶做規畫，與客戶建立非常密切的關係；並配合對人才的訓練，以合理的報酬留住人才，台揚是少數高科技公司中推出股票選擇權的公司，並開辦員工持股信託。

未來無線通訊仍會出現大幅度的成長，台揚將可望爭取相當大的商機，而無線與有線的整合是台揚在未來將追蹤的發展。

Above: From a Newspaper in Hong Kong, 1987

Left: Global Marketing!

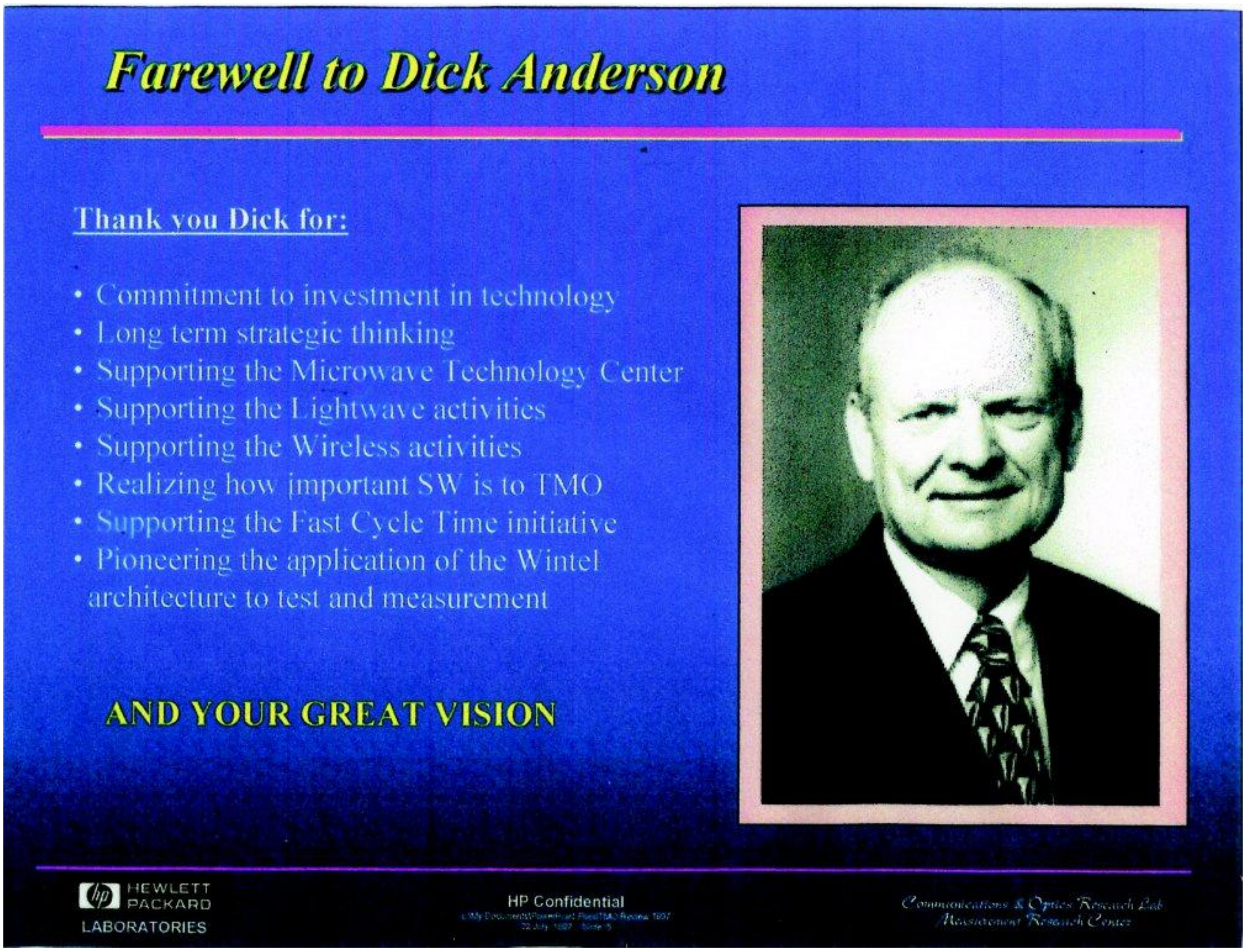
Over the fourteen years that I was the General Manager of the Microwave and Communications Group it was my privilege to work with and be supported by some very capable and dedicated people. The division managers included Bill Wurst, Byron Anderson, Duane Hartley, John Shanahan, Alan Seely, Rod Carlson, Al Steiner, Doug Scribner, Finley McKenzie, Ned Barnholt (who became my boss), Jim Olsen, Deborah Dunn, Scott Wright, Jim Rundle, Yoh Narimatsu and Don Summers. Staff members included Gil Reeser, Bob Allen, John Page, John Lemley, Marc Saunders, Russ Johnson, Chuck Acken and Candy Wehrcamp. I know some have slipped my mind after 23 to 37 years, so maybe some of my long time HP associates can jog my memory. I want to add here that I am forever grateful for the contribution and support of all of these exceptional people and for many others too numerous to list.

Over these wonderful years the group was always at the top of the company's profitability rankings. The group showed reasonable growth in spite of substantial decline in the traditional defense-based markets. This came from making valuable contributions in exciting new areas. Through it all, technological advances continued their historical pattern of excellence. I feel very honored and privileged to have been there. It was Camelot for sure!

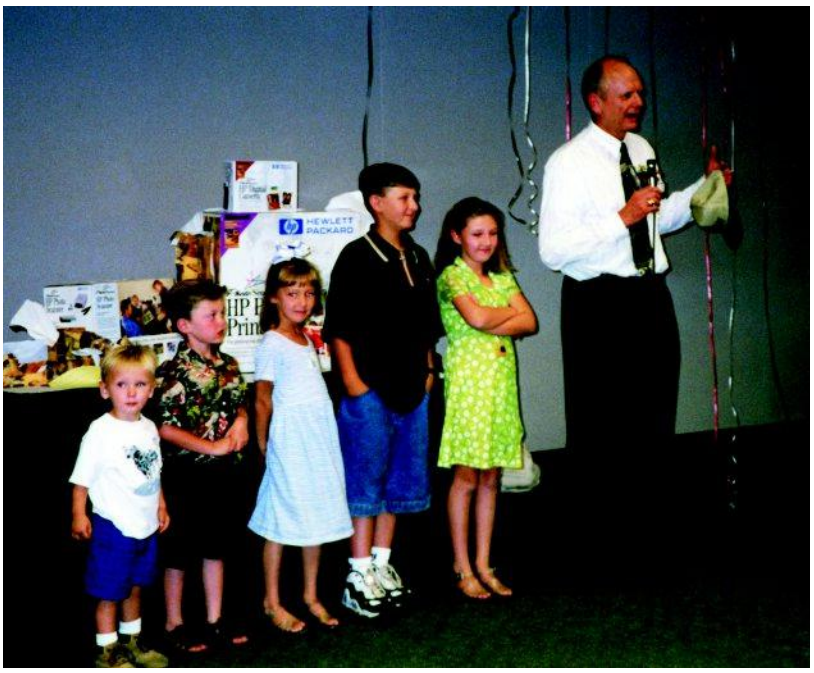
During my years at HP I served on several external and internal boards including Conductus, Wireless Data, Gerber Scientific, Microcircuit Technology Inc., Hewlett Packard Ltd. (UK), HP India, and The Cupertino Chamber of Conference. Early in my career I was active in the Institute of Electrical & Electronic Engineers (I served in several elected offices).

In August of 1997, I formally retired from Hewlett Packard. I was honored by several friends and associates from all over HP worldwide. I am including some excerpts as part of this history. If you look through them please do it with the understanding that the lucky guy was me. I was blessed to work at the finest company in the world, founded by the two greatest leaders ever and employing the greatest work force in history.

Retirement event with HP Chairman Lewis Platt.



Top: A very kind farewell from the corporate laboratories.



Right: Grandchildren at retirement event. Left to right: Devlin, Riley, Whitney, Tyler, Alexa

Selections from Richard's Retirement Album

Dick, when I think of the times I worked under you, no one event brings back more memories than the divestiture of the Palo Alto Fabrication Center. I have heard Lew Platt speak on two occasions where he specifically credited the success of this complex divestiture to the leadership of the management team. A team that was led by your sense of balance for what was fair for our shareholders, our customers and our people.

I will never forget sitting in Lew's staff meeting as you reviewed our plan, and having Lew ask who the heck ever recommended to put ALL PAFC employees on the excess list for VSI. If you remember, we decided to do this because we knew we would be announcing the plans to shut down PAFC right after the VSI announcement in 1992. Based on the way Lew asked the question, I though this might be one of those career defining moments, but before I could tell Lew that I made the recommendation, you jumped in and explained why WE made the decision. I really appreciated your support in that situation.

The PAFC divestiture is history, but the way we approached it has served as a model for most subsequent divestitures in HP. Thank you for setting high expectations and your unwavering support for achieving the right balance between what was right for our shareholders, customers and our people. Many people call it a class act. I call it the result of working with a class leader.

I wish you health and happiness in your retirement. I have certainly learned from your example and will apply what I have learned.

With fondest regards,
Doug Haller

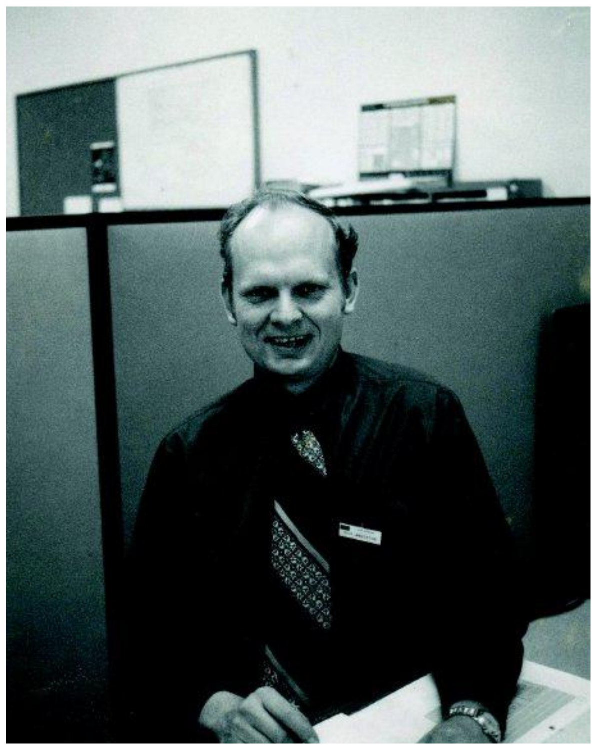
Dear Dick,

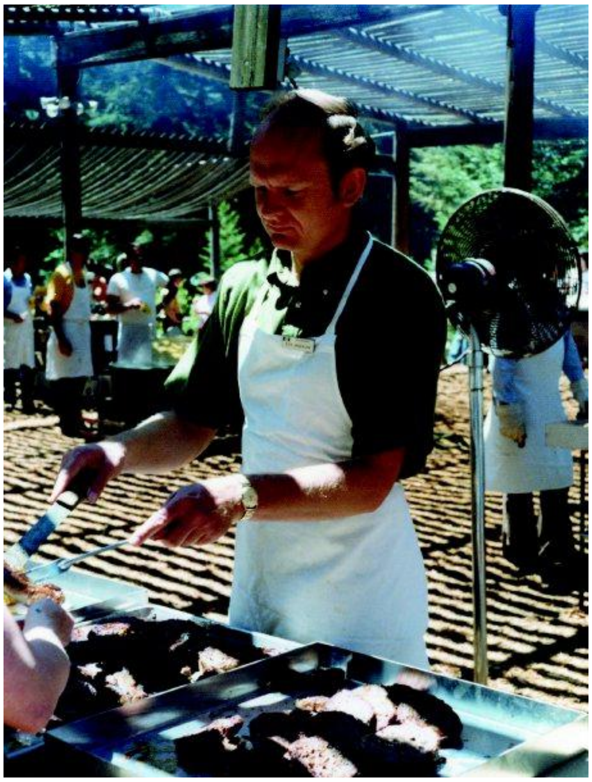
I regret that I will be out of town on the day of your retirement party. I'll miss seeing you and a lot of old friends and also learning of the fortunes of MTI.

I clearly remember the day I drove down to Cupertino to ask you to leave the glamorous world of computers and remember my pleasure when you said yes. You have kept and improved one of HP's strongest business and consistent profit contributors. I also appreciate your personal effort in making the microwave group an exciting place for many at HP.

I know you're going to enjoy the next career and I hope to see you soon.

Bill Terry





Cooking and serving steaks at a company picnic at Little Basin. 1971.

Hi Corny,

Back in the early 70s (1973 I believe), we had just moved into Bld 70 on Arques and I was coaching the division's softball team. At the division picnic at Little Basin that year I had formed two teams for a softball game and Dick played with us. Back then the ball field was down near the parking lot and there was a huge oak tree in dead center field. Most of the out fielders played in front of the tree because no one had ever hit the ball that far. I'll never forget when Dick came to bat and he promptly hit the ball OVER the tree. That Monday I cam into Dick's office and asked him if he would like to play on the division's team in the Industrial League in Palo Alto. Of course he politely declined due to time constraints, but I always thought he could have been the Mickey Mantel of our league.

Jim Bechtold

Dick:

When we first met, at an MDS review in Santa Rosa in the Summer of '93, I thought to myself, "This is a really beautiful setting; it's remarkable that people are getting paid for working here." Now I'm one of those fortunate people. And the beauty of the workplace isn't confined to its geography. HP-TMO in Santa Rosa is a technically strong, commercially successful organization of people who value excellent performance and personal responsibility. That description is a credit to the organization's leadership.

Thank you.

For everything.

Hans Mattes

Dick,

Congratulations on your impending career change:

HP Spotlight

1. Dick Anderson to retire, Bryon Anderson to succeed at MCG

Dick Anderson, HP vice president and general manager of the Microwave and Communications Group (MCG), will retire in August after 38 years of service with the company. He will be replaced at the helm of MCG by Byron Anderson, currently HP vice president and general manager of the Communications Test Solutions Group (CTSG). Tom White, general manager of the Computer Peripherals Bristol Division (CPD) in the United Kingdom, will succeed Byron Anderson.

I have enjoyed your help in several TMO efforts, including Motorola and Northrop. Thanks for everything...

Wishing you and your wife many happy times...

Bill Fritz, FE/TMO

Dear Dick:

Let me be one of the first to congratulate you on finishing an outstanding career at Hewlett-Packard. I have had the pleasure of knowing and working with you for quite a number of years, and I know this retirement is well-deserved.

I'm sure there will be a number of events regarding this soon and I look forward to attending at least one of them. I hope you and Moon-Yeen enjoy this new "adventure" in your lives.

Best personal regards,
George Cobbe

Greetings, Corny:

In response to Ned's note on Dick's retirement, I offer the following account. It may or may not be appropriate—you be the judge.

Back in the early seventies when Dick was GM for the Automatic Measurements Division, the division had a number of military contracts. Equal opportunity was the 'Affirmative Action' of the times, and we were told to expect an EEOC Inspector. All of the supervisors were gathered into our large conference room for a briefing by Dick.

When asked how we should respond to queries from this Inspector, Dick told us, "Be frank. Tell it like it is; call a spade a spade." Of course, the room erupted in a gale of laughter. Startled and taken aback, Dick said, "What did I say, what did I say?"

I'm sorry that I will miss the big reception for Dick, as my daughter and her family arrive about then from Pittsburgh, PA. Please convey my best wishes. I'm sure he will as busy in retirement as he is now (that has been my experience the past seven years).

Take care of yourself—
Bob Knapp

Hello Corny—

I can't believe so many of us still work for Hewlett-Packard after all these years! Guess that says some really good things about working for this great company!

I won't be able to attend the festivities, but I do remember an incident with Dick that for me was memorable. This happened shortly after I joined HP in late 1975, and if my brain hasn't failed me and I have the person right, it involved Dick and a swarm of bees. (I think it was Dick...Dick Love / Dick Anderson???)

I sat in Building 40 (when it still existed!), right next to the windows on the west side of the building. One day during the summer some bees began to swarm in one of the trees right outside my window. A number of us had watched with interest for a while, when all of a sudden, a wagon pulled up and out stepped Dick, all decked out in bee paraphernalia from his helmet to his heavy duty glove! Since I've always had an aversion to bees, I was fascinated that anyone I knew would be interested in retrieving their busy little bodies. What amazed me even more was that someone who was a high level manager in this international company I had just joined would don his "grubbies", and in front of everyone, scoop up this squirming mass of bees. I realized then what a people-oriented company I had just joined, if a manager at that level was willing to step out and just be a human being, enjoying what must have been a hobby for him.

So Dick, if my brain didn't fail me and it was you who scooped up those bees, I think you proved to me that day that the core of HP is it's people, and that I wasn't working with a bunch of "machines", but with warm, human beings. I hope you have many wonderful plans for your retirement and if you still keep bees, may your bees continue to prosper!

Best regards,
Kerry Pottery

Hi Corny,

Thanks for inviting contributions of Dick Anderson reminiscences!

I worked in Dick's organization for only a brief time in my HP career, but, nonetheless, he had a very positive impact upon me.

Dick probably recalls the dates better than me, but I believe he became F&T R&D Engineering Manager sometime in 1968. At that time, I had been with HP about two years, and I was only 24 years old. I was married and a father, but Dick looked and seemed so much older and wiser than me. Looking back now, I realize he must have been in his early 30's, but he might as well have been a senior citizen, as far as I was concerned!

As part of the DSA group, reporting into Skip Ross (through Charlies Trimble), I worked down the hill in Building 11, while Dick and most of his team resided in building 5M. With my first presentation to Dick, just prior to a scheduled B Checkpoint meeting for the Correlation Synchronizer addition to the 5480A Signal Averager, I recommended to Dick that my project be cancelled. That was a very scary thing for a young engineer to do, but Dick accepted the recommendation and gave me positive feedback. Dick Anderson Lesson #1: Tell the truth and do what is right for the business, and all will be well.

Shortly thereafter, Dick decided to bring back the DSA R&D team to 5M so that all the engineers could work together. Dick Anderson Lesson #2: Teamwork is a core value, and it works best when the team members are co-located.

I think we were still in 5M when Dick, Skip, and, I think, Jim Doub, invited me to an evening meeting at the old Cabana Hotel on El Camino Real. Room service dinners were ordered, and it quickly became clear to me that I would not be allowed to go home until I had agreed to their proposal that I become the Signal Averager Project Manager (Charlie had transferred to the IC Tester program). So I decided I had better go along with "the program." Dick Anderson Lesson #3: Drop down as far as is necessary (it was three levels from Dick to me) and give your personal time if you want to demonstrate your concern for employee and business welfare.

It was 1969 or 1970, and Signal Averager family sales were lagging. Dick had contacts with Microwaves magazine, and he volunteered Skip, Jim, and me to co-author a microwave application paper with him for publication. Dick Anderson Lesson #4: Leverage your previous experience for current returns.

The last encounter that I recall occurred in 1971. At the time, it was a somewhat negative happening, but the long-tern consequences were very positive. Another Project Manager approached me with the statement: "I understand you are looking for a job." Actually, I was not, so this statement was very upsetting. I talked with Skip, and he referred me to Dick. After about 20 minutes of discussion, I asked Dick if he wanted me to try something different. He responded affirmatively. With that advice in mind, I accepted a project management position in Logic Test R&D. Two years later, I moved to Personnel, and later transferred to Quality and then Manufacturing. While that initial job change could have been handled more gracefully, Dick successfully implanted in me the need to change responsibilities periodically. Today we would call that concept "Career Self-Reliance." Dick Anderson Lesson #5: Manage your own career before somebody else does it for you.

I thank Dick for all the help and guidance he gave me, and I wish him the best as he enters this next stage in his career.

Best regards,
Chuck Taubman

Dear Dick,

Congratulations on your upcoming retirement. It has been a real pleasure to work with you on the College's Advisory Board for the past several years. I hope that your "new-found freedom" will allow you to spend more time here in Cache Valley. We really enjoy your company.

Dick, I have really appreciated the kindness and hospitality you have shown to me over the years. You have been a very good example of how people who are busy and with demanding schedules can still take the time to talk on the phone, have dinner, or just visit. Of course, your support of our College in helping to sponsor or write letters of support for proposals to HP has been a great help to me in doing my job. I also appreciate your being a reference for me when I applied for a new position. I have also enjoyed getting to know your family; they are great.

Your leadership and style have always been a guide to me. It is no wonder you have done so well in every aspect of your work and other activities. You have been and are a great example.

I have also been impressed with your business knowledge and your view of the future. I'll always remember your speech to our engineering students about three years ago when you said how much our lives would be changing due to the electronic modes of interaction that were on the horizon. (Almost no one had heard of the web at that time.) Virtually everything you predicted has already happened.

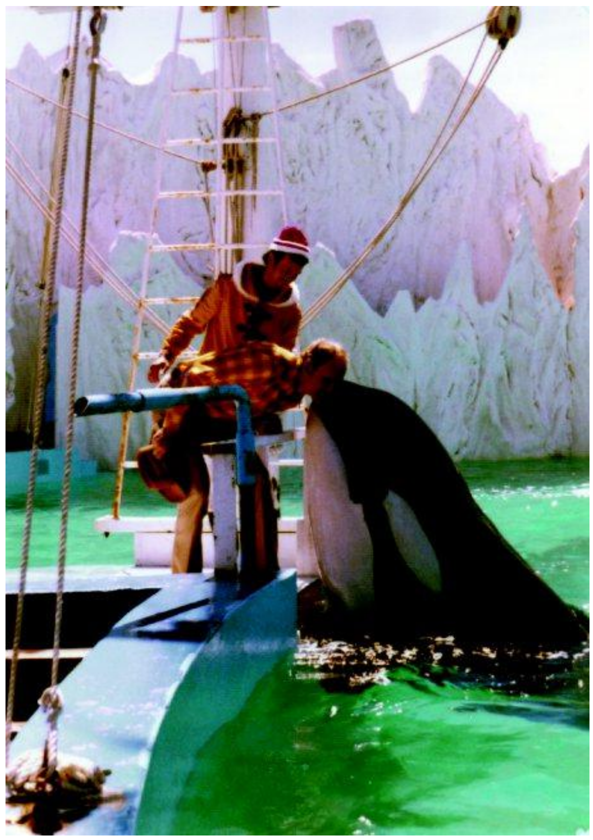
It has been great to have you as a friend and associate. May I wish the very best to you and Moonyeen during the approaching years. I hope to see a lot of both of you.

Sincerely,
Robert L. Davis
(University of Utah)

Dick,

Retirement is just another job change but with more flexible time. Congratulations on your 38 year career at HP; it certainly must be a proud moment for you when you review all the accomplishments. The Spectrum Analyzer will always be one of the most memorable for me and I can still remember you at the bench working on the mixer (2GHz!). It was a great product family then and still is today. On a personal note, I want to thank you for the many times that you were there to support me. Our paths did cross quite often and I was very fortunate to have worked with you. Again, congratulations to you and Moonyeen on your retirement. Jane and I wish you both the best in the years ahead.

John Shanahan



Providing entertainment at the company outing at Marine World.

Dear Dick:

I can't believe you are really leaving! I've worked for or with you for 25 years and have always respected you. It is a great loss to HP to have you retire. You will be sorely missed.

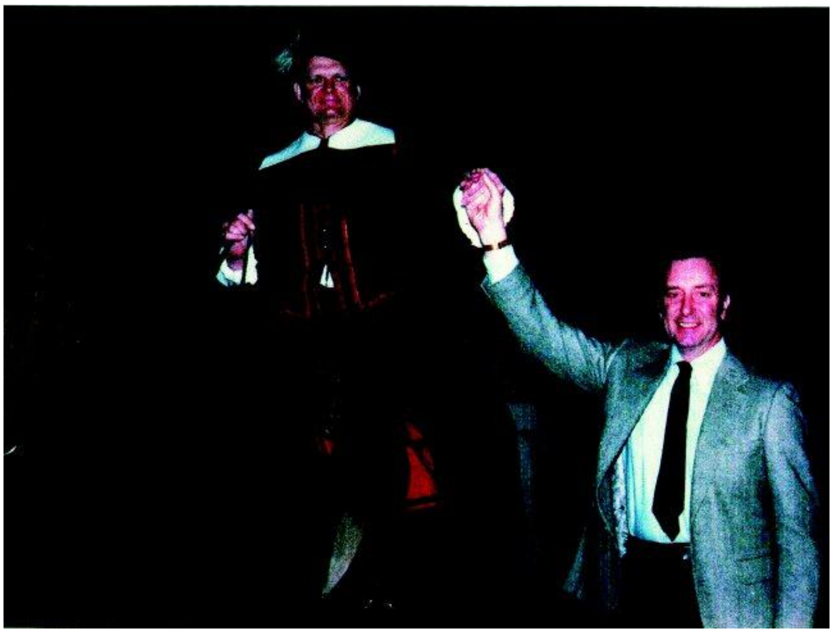
I wish you and your family the very best. Please take care and God bless.

Best regards,
Ray Drost

Dear Dick,

I am sorry to miss your going away party, but Lynn and I will be in Scotland on a holiday. You and I have worked together for well over twenty years, and I look back on my HP days now with very fond memories. I know you will too. Remember, old cowboys never die, they just ride off into the sunset!

Best Wishes,
Gil



As Louix XIV with my good friend and boss, Paul Ely Grenoble. France 1979.

Dear Dick,

Congratulations on your retirement. I hope you and Mooneen enjoy it as much as Carol and I have. I have especially fond memories of the time we worked together at AMD, plus all the other times we had interactions. Sorry we couldn't be there for the formal event. I am sure it will be a wonderful event. Enjoy!

Sun Valley is on the way to Montana, so please come by and visit.

Best Personal Regards,
Ben L. Holmes

Dear Dick,

Corny called, and she wondered if I would contribute something to the scrapbook she's putting together. Well, I am honored, and hope this is not too late to be included in the book. But where to begin...

A bus ride to Miramar outside of San Diego. I was doing what passengers not engrossed in conversation often do (unintentionally, of course); I was hearing bits of conversation from those around me. Public Education was the discussion of two gentlemen behind me, and neither was impressed with its current status or eventual product. Though to hear from anyone, but when I found out later who the men were, I was concerned. It stayed with me for the next few weeks, so I asked Tim if I could write the gentlemen a letter. That poor guy has to live with me, knows how passionate I am on the subject of quality in education, and no doubt decided it'd be better in the long run, so to heck with any future promotions!

You graciously accepted my invitation to come to the Tustin School District, truly impressive when considering how busy you were at the time. After all, we don't even know one another on a professional basis let alone a personal one. Dinner was good, and I learned about your many business trips to Asia, including a side trip to see the Cian pottery soldiers in China (my Ancient Civs class thought you must be incredibly wealthy to have seen something depicted in a history text!). You shared a bit about your personal life, including Tina's studies toward a degree in education and Moonyeen's prior teaching experience. In short, you put me at ease.

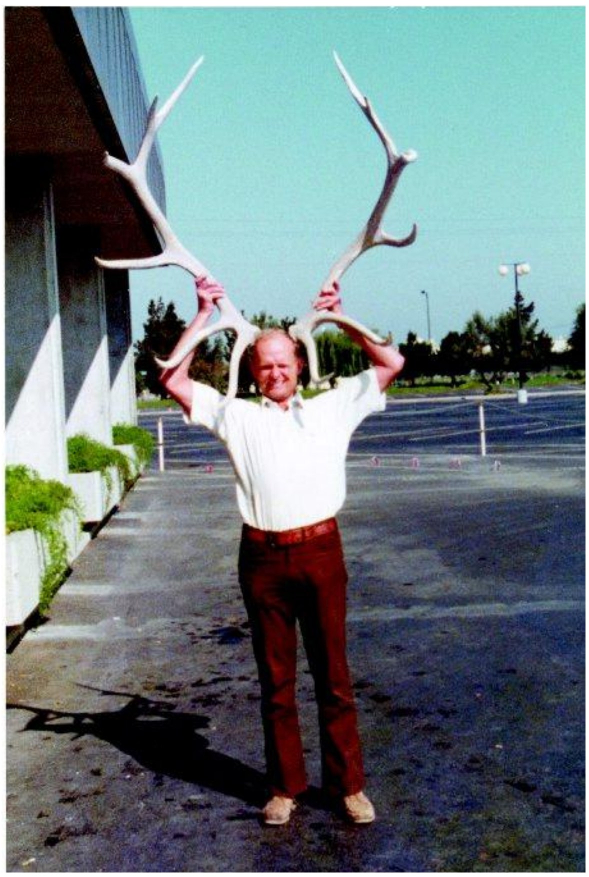
We went to a few schools in Tunstin and spoke with some of the administration. After talking again at lunch (cold pizza), it became clear that we were not as far apart in our perceptions about education as I had originally suspected. As a fact, we agreed that the current system is in need of revamping, and perhaps the most intelligent evolution at this time is to approach it as more of a business. I'm glad we were able to spend some time together outside the HP arena. I learned what the perspective of education is from a businessman's point of view, and I remain hopeful. The biggest surprise in this whole scenario was finding out just exactly where you ranked in terms of management (Yikes! I've never known anyone so important), and the generosity you displayed in personally funding the purchase of the Hewlett-Packard Printers for the Tustin Schools.

We ran into one another at this most recent Winner's Circle gathering, and I enjoyed visiting with you about recent developments in both Tina's careers and David's developing interest in photography (video and film). I was inspired to hear how Moonyeen handled the discouraging words about future employment by one of Tina's professors and how she addressed the issue with him. It's amazing how much I've learned from our short acquaintance.

Our most recent contact was when you agreed to write a letter of recommendation for me. You responded to yet another of my requests without hesitation, and I'm confident it will result in my future employment. I'm glad I was able to spend time getting to know you. You're an honest man with true integrity, the finest qualities any man can have, I think.

Enjoy your retirement, Dick. If you're ever in Phoenix, please look us up. We'd enjoy having you and your wife as our dinner guests.

Sincerely,
Peggy Cartier



After a hunting trip in Wyoming with another employee.

Dear Dick,

After so many years with HP I am sure you must have hundreds of letters wishing you "All the BEST".

I want to thank you for all the conversations over the years. You have always been very approachable, candid and full of that rare commodity: common sense. In particular I appreciated your sense of the difficulties the small countries face when living inside the BIG HP machine.

Your efforts to keep the flame going in the dark days of 1985-87 sales force 15 was an inspiration to me and all of the troops. I know how much courage that took at your level. Thank you.

I do not forget that through your leadership and contributions my stock in HP has educated my children, has given me wonderful experiences and will provide Ana and I a very comfortable life after HP.

I would not like to lose touch with you and your family. Even if it is only to exchange Christmas cards. When the dust settles and you all have decided where you'll live I would like to hear from you.

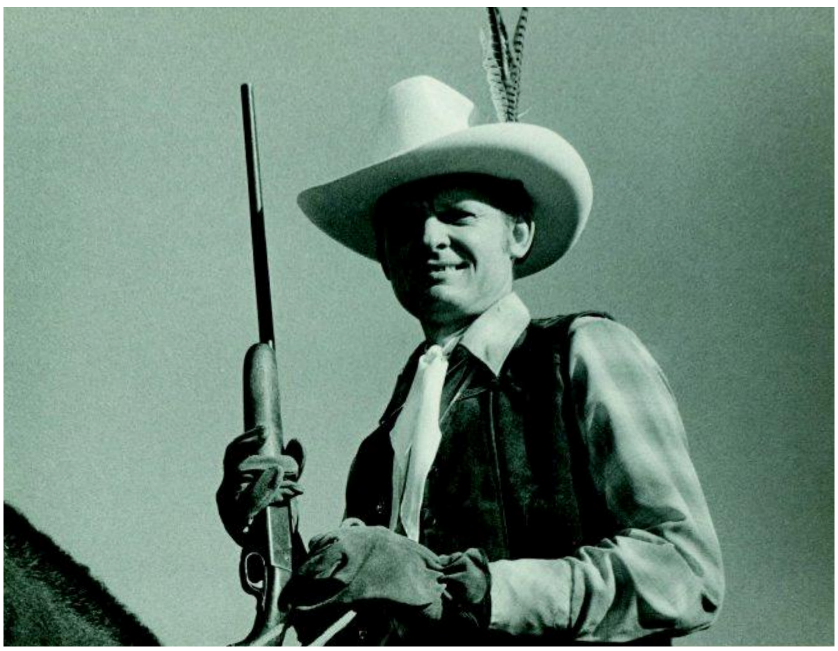
I wish you God Speed! May you always have the wind to your back and the face to the sun.

Warm person regards,
Bill Woehr
Geneva Switzerland

Greetings Dick,

I just wanted to send you my best wishes on your retirement. From my personal experience (over 7 years) I know that you will enjoy it and be even more busy than you are now. There isn't enough time to do everything! So do what YOU want to do and the rest will take care of itself.

Best regards,
Bob Knapp



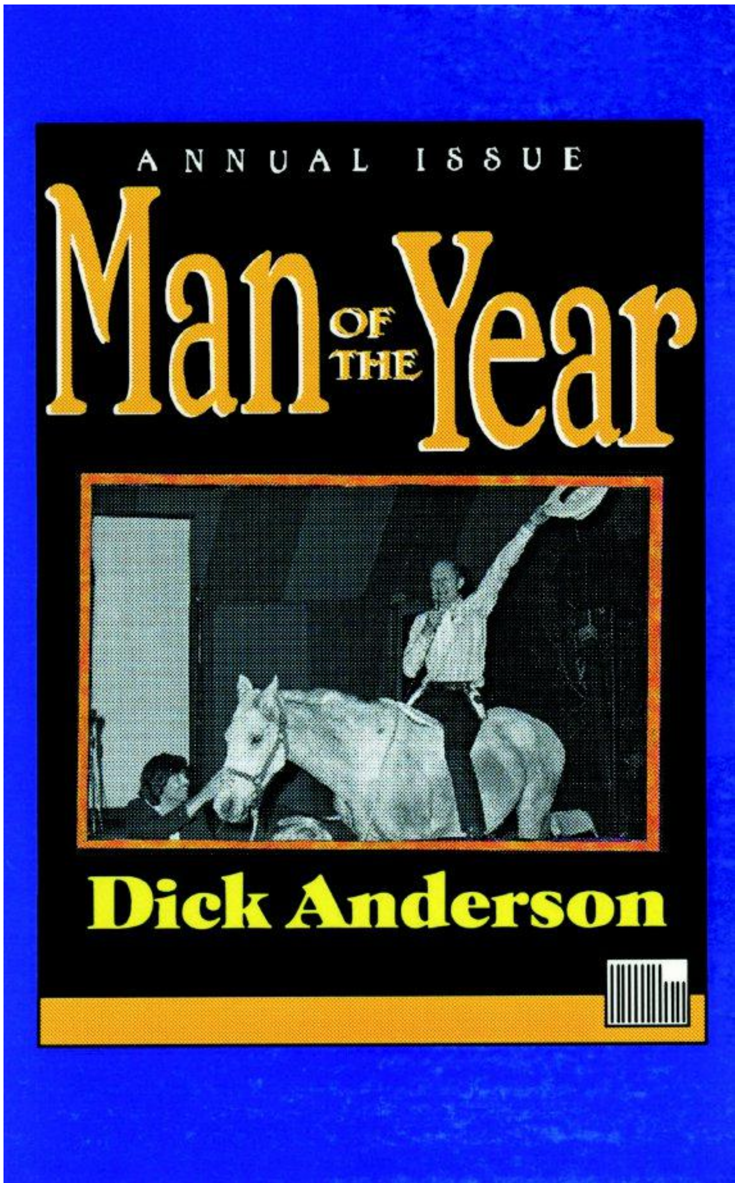
Leader of HP Posse! Work should be fun!

Dick, Byron:

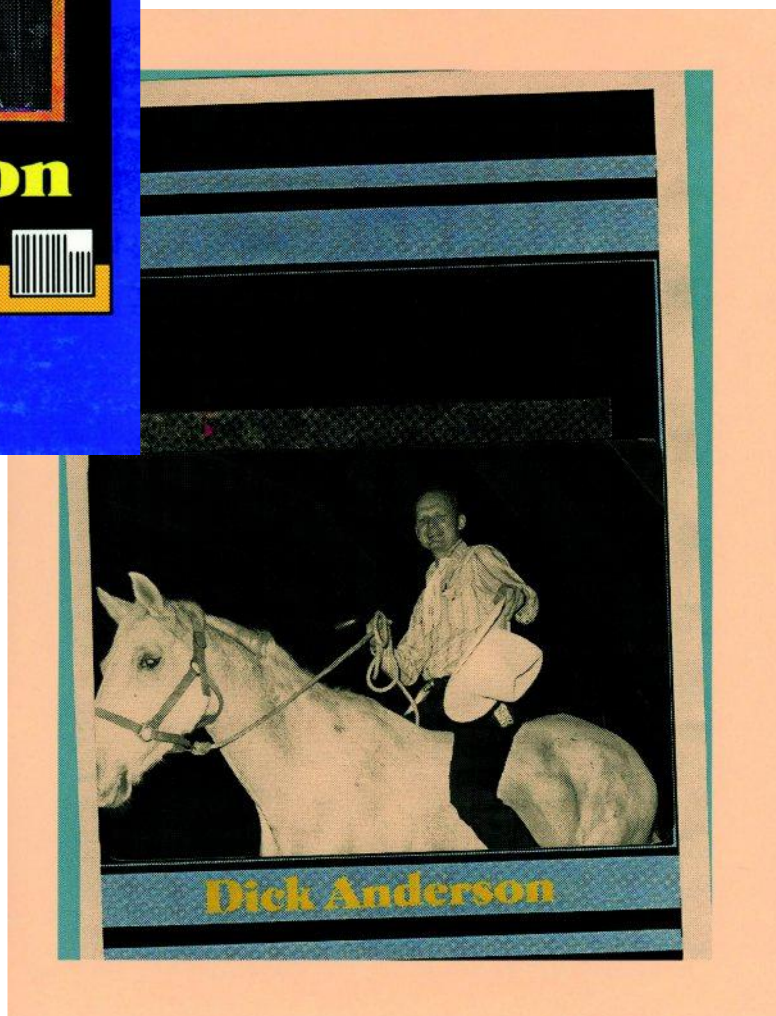
Congratulations to both of you on your respective moves: Dick, it's been great to work with you through my days in SPD and VID, and I hope you have a great time in your retirement. 38 years... Wow!

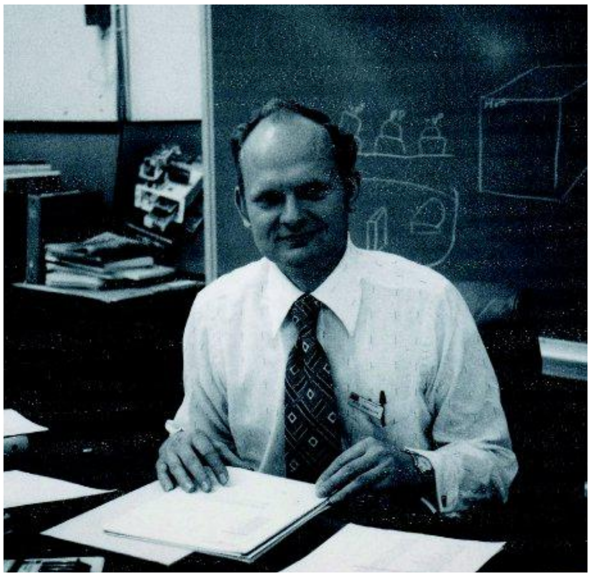
And Byron, best wishes as you move in to the MCG slot, and I'm sure you'll be able to provide the same great leadership for growth that you've brought to CTSG.

Best Regards,
Dana Kreitter



Managing on Horseback!
Round em up, Move em out!





Rare time at the desk, circa 1990.

Hi Dick,

As I read the announcement about your retireing, I had to send you a note. You had indeed had a very distinguished career at HP, and I am among the very many that greatly appreciate not only what you have accomplished, but also the manner in which you did it.

I haven't heard yet whether or not you have any specific plans for "life after HP". Our mutual associates tell me that:

- it really exists!
- the first Monday after retirement is the worst day.
- the greatest danger is that you will be too busy.
- you will wonder how you ever had time to work!

Whatever you do, I hope that the future is full of pleasant and fulfilling days for you and Moonyeen.

Best Regards,
Bill Kay

Please read this at the party:

Dick, please accept our sincerest thanks for your active support, encouragement and advice over the years. Your keen eye for detail, always on the prowl for opportunities, identified our need for microwave CAE focus a number of years ago – which subsequently has yielded much fruit. Your close questioning during Business Reviews always kept one alert and hence well prepared.

All of us in Canada again say a big thank you for your very direct involvement in the Purchase of Idacom, bringing a greater HP presence in our country which has provided jobs, excellent products and clearly demonstrates the Canadian Government HP's commitment to Canada. This has resulted in HP attaining favoured supplier status.

As a token of our thanks and to recognize the many outstanding contributions you have made to Hewlett-Packard's success over your 37 years please accept this book on Canada and we also bestow upon you the position of Honorary Canadian Field Engineer. (P.S. if you're looking for a part time job I'm sure we can carve out a territory for you with lots and lots of quota!!)

Dick on behalf of everyone in TMO Canada we wish you and Moonyeen many many healthy and happy retirement years.

From all your friends in the Great White North,

Alan Holdway

Hi Dick,

I am unable to stop by tomorrow afternoon but wanted to wish you well as you retire from HP. TMO has benefitted immensely from your visions on the future capabilities of technology. Your departure will leave a big void.

Best wishes in your new endeavors.

Becky Porter

Hi Dick,

I first want to thank you for hiring me into the F&T Division in 1969, and providing me some good coaching, support and advice several different times during my first years at HP.

I hope that you will enjoy this new phase of your life that you are beginning.

Sincerely,
John Stedman

Dear Corny,

Unfortunately, neither Carol nor I will be able to be in California for Dick's retirement. Please wish him and Moonyeen all the best from us.

As far as memorable events, there were many, here are just a few:

Dick's greatest fear: having to sign Joe Schoendorf or Bob Brannon's expense report.

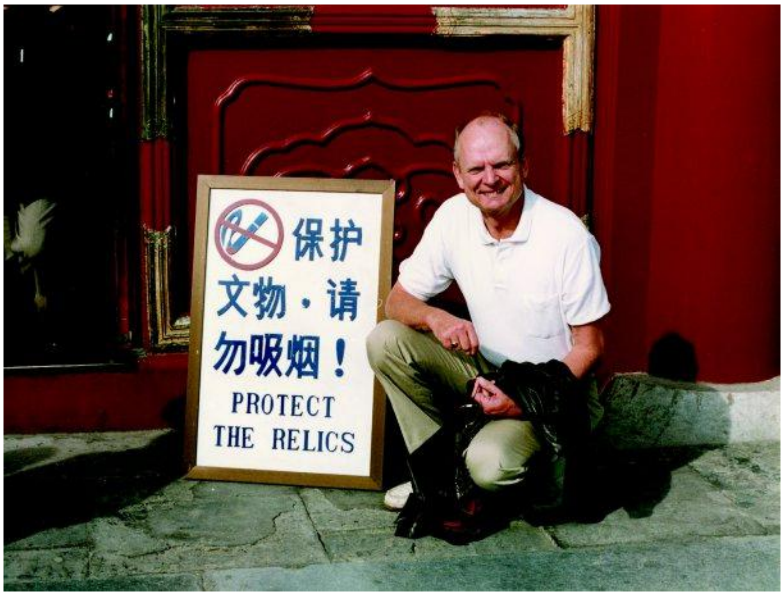
After one trip to Europe, Dick asked Joe how he could have spent as much money as he had. Joe replied, "Only if you have small breakfasts, and order wine with every other lunch."

My best memory of a Dick and Joe's interaction is from a dinner we had an AMD for the then sales force 5. The new computer systems and organization had been formed but not announced, rumors were flying, but only a very few of us knew what ould happen. Paul invited himself to the dinner, and asked to speak to the AMD folks and to sales force 5. Joe was the host and was asked to introduce Paul as the Data Systems General Manager who assured him... "he had no territorial interests past Poland."

Dick was a great boss; we had lots of business successes and fun at AMD. The computer business was new, we were all kids, and had a great time. Many of the remembrances of those times are better left remembrances.

Probably my fondest personal remembrance of Dick involves Carol. Carol was offered the Microwave Marcom job while we were dating. After Carol took the job, Dick noticed I was hanging out around his group headquarters a lot. Since MPG had little to do with Microwave, he thought it somewhat peculiar. He told me later he had guessed our relationship, but had the sensitivity to keep it to himself. However, when Carol told Dick we were getting married and moving east, Dick warned Carol that I was a rather stubborn individual. Carol reported the conversation to me. The next time I saw Dick, I mentioned it to him, and stated, "That really is the pot calling the kettle black."

Sincerely,
Ben L. Holmes



Forbidden City, Beiing, China. Circa 1990.

With longtime, wonderful secretary, Corny Sluis.

Corny,

Sorry to be so late in responding, but I was trying to rearrange some schedules and wasn't able to work out attending. I do have the following story regarding the "miracles" of Dick Anderson.

Dick was good at customer calls and helping us close business. He visited Dr. Q. Balzano, a VP of Engineering and assured him that our uW CAE offering was the best in the business. We received several orders for the software along with the new "Risc" work stations from the Computer Group.

When Motorola couldn't get delivery, we had him visit with Walt Davis, a VP responsible for the IC development group and ultimate responsibility for the "Risc" decision. Walt needed to have Hewlett Packard new RISC architecture "spectrum" computers for his engineering group delivered in a HURRY.

Dick was able to get him the first two commercialized units before anybody from the Computer organization could do it. That convinced me that Dick could do two "miracles" per year.

My only question was, "Why didn't Dick move up the ladder in the Computer Group with power like this?" Maybe the answer will come out of someone else's war story. You will have to solve the mystery for me. I am really sorry I won't be able to attend.

Thank you for thinking of me.

Regards,
Bill Lovelace

Dick's association with Queensferry goes back a long way, back to the late sixties when Dick visited what was literally a green-field Queensferry site, on one leg of the 8410 Network Analyzer European introduction tour. Over the years, Dick's become a 'weel kent' face in Scotland, working first with the original Telecom Division, before going on to make one of his canniest and most successful HP investments with the start up of QMO in 1984.

As QMO Founding Father, Dick nurtured the fledgling operation through the tricky early years when so many start-ups founder. Dick has been a steadfast sponsor—even in years when business conditions were tough.

In 1992 Dick elevated QMD to Division status and laid the groundwork for five years of greater than 30% annualised growth rate.

Dick has always enjoyed a special relationship with QMD. Dick's bold vision for the Division succeeded beyond what any of us had dreamed of.

Dick, from all at QMD, our warm appreciation for your special contribution to our success and our best wishes on your retirement.

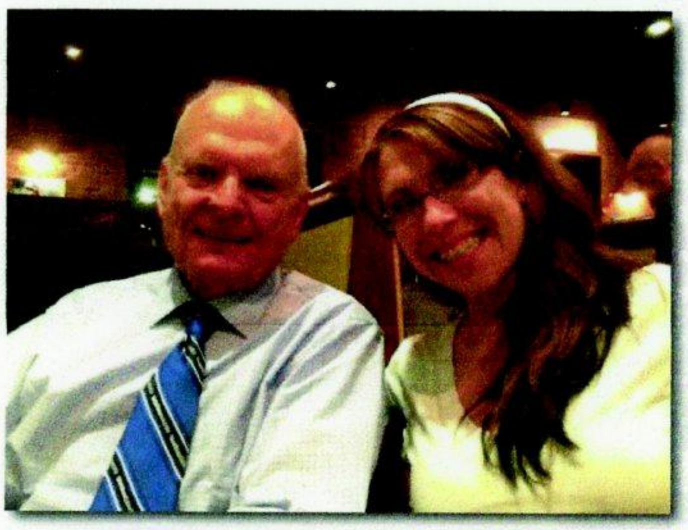
Haste ye back -
from Bill Savage and the QMD Team

My Return Visit to HP in 2000

In 1999 Lew Platt retired as Chairman and CEO of Hewlett Packard and the Board hired Carly Fiorina as it's new CEO. It became immediately obvious that the company would never be the same. In early 2000 Ms. Fiorina invited many retired HP executives to a meeting in the Cupertino Auditorium. I took the opportunity to join the meeting. After the meeting concluded I took the opportunity to have a several minute discussion with Carly.

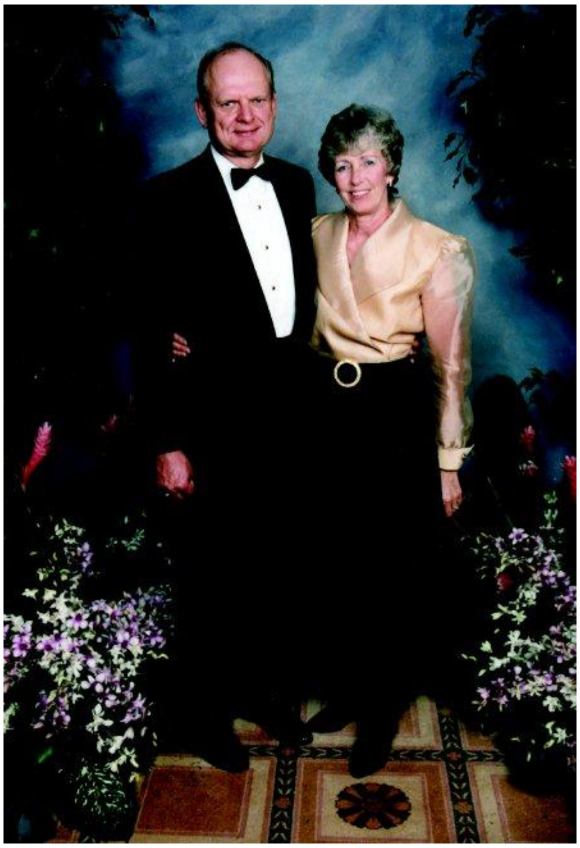
When I got home I decided to call Dick Hackborn at his home in Boise. Dick and I had worked together over many years, first on Automatic Network Analyzers and then in the Computer Operations. After exchange of pleasantries and a few laughs from old times, I told Dick where I had been and why I was calling. My message was four words: DON'T WAIT TOO LONG! I then explained that Carly was not a fit for the HP CEO job. Sooner or later she would have to be let go. Again, DON'T WAIT TOO LONG! My observation from the meeting was that her values were orthogonal to HP values. Orthogonal values will never get to satisfactory results. Sadly the HP Board waited too long. Momentum lost is impossible to retain.

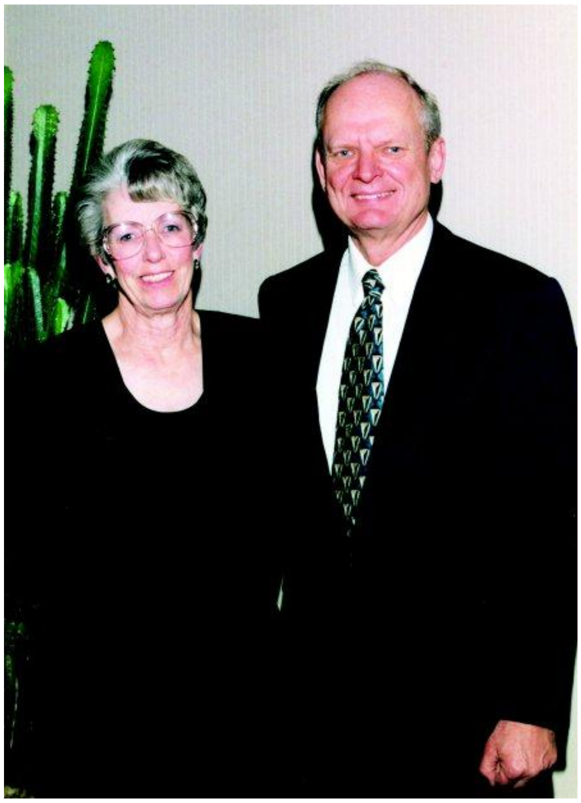
Sept. 23 - 24: Logan, Utah. Met with old HP boss, Dick Anderson, and did a presentation at Utah State University to a combined audience of engineering and MBA students.

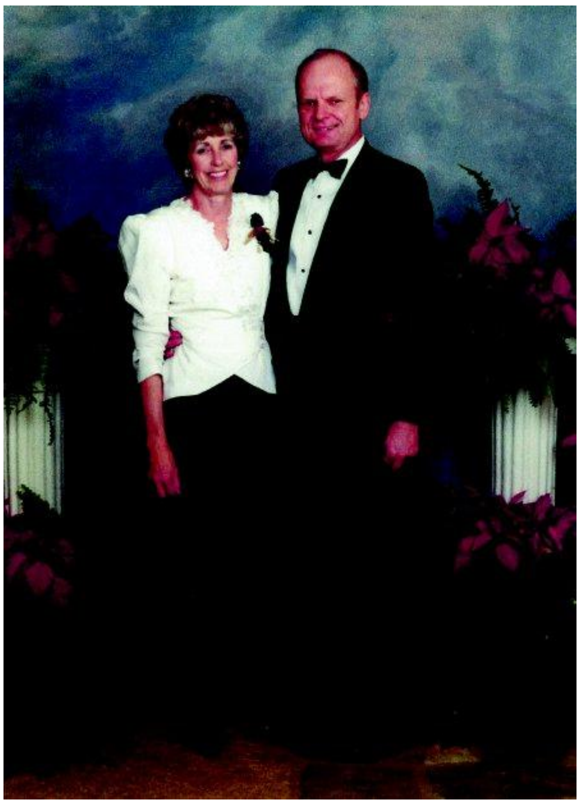


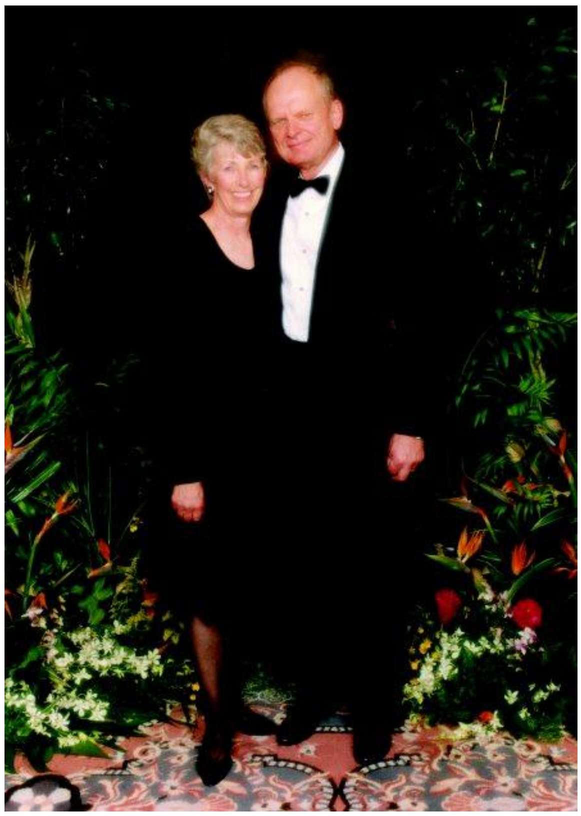
Over dinner, Dick shared fabulous stories about his time at HP. One of the students, Kristen Sims sat next to Dick and soaked up his stories. I asked her what she got from the evening. Her response was remarkable:

"It was his humility, his view of leadership and the fact that he was part of HP during the 'golden age' that we've used as case studies in my MBA program." She continued, "I met a legend tonight. Now I want to go back and read those case studies again. The world became a little smaller. Someday I'll look back on today and realize I sat next to the great man."









Richard and Moonyeen at President's Club dinners through the years.

Two Significant Technical Papers

During my career as an engineer and manager I had the opportunity to work with some very interesting and important technologies. Some that I will mention include digital computers, integrated circuits, computer software, computer networks, fiber optics, automatic test and measurement, linear and digital circuits, signal analyzers, microwave devices and computer aided design. Over the years I wrote or presented papers or reports on most of these and many others. I am presenting here two of the most significant technologies that I was involved with. In 1966/1967 I authored and coauthored these papers presenting the world's first really capable microwave network analyzer and a companion paper on how to effectively utilize network analyzer measurements to design wireless devices and systems. These capabilities truly revolutionized the wireless world.

Without this first network analyzer and others that followed it is very unlikely that there would have been such remarkable innovations such as global position satellite systems (GPS), stealth aircraft, fast radar, sophisticated cellular networks and powerful smart phones. And, fifth generation networks (5G) with such things as self-driving cars would just be a pipe dream. It is with profound satisfaction that I present these two 1967 papers so that you, my descendants, can know what your grandfather spent some of his time thinking about. After all, you are the ones for whom this project was undertaken.

Richard Watkins Anderson
April 15, 2021

APPLICATION NOTE 95-1

HEWLETT PACKARD

S-Parameter Techniques for Faster, More Accurate Network Design

ABSTRACT. Richard W. Anderson describes s-parameters and flowgraphs and then relates them to more familiar concepts such as transducer power gain and voltage gain. He takes swept-frequency data obtained with a network analyzer and uses it to design amplifiers. He shows how to calculate the error caused by assuming the transistor is unilateral. Both narrow band and broad band amplifier designs are discussed. Stability criteria are also considered.

This article originally appeared in the February 1967 issue of the Hewlett-Packard Journal.

LINEAR NETWORKS, OR NONLINEAR NETWORKS operating with signals sufficiently small to cause the networks to respond in a linear manner, can be completely characterized by parameters measured at the network terminals (ports) without regard to the contents of the networks. Once the parameters of a network have been determined, its behavior in any external environment can be predicted, again without regard to the specific contents of the network.

S-parameters are being used more and more in microwave design because they are easier to measure and work with at high frequencies than other kinds of parameters. They are conceptually simple, analytically convenient, and capable of providing a surprising degree of insight into a measurement or design problem. For these reasons, manufacturers of high-frequency transistors and other solid-state devices are finding it more meaningful to specify their products in terms of s-parameters than in any other way. How s-parameters can simplify microwave design problems, and how a designer can best take advantage of their abilities, are described in this article.

Two-Port Network Theory

Although a network may have any number of ports, network parameters can be explained most easily by considering a network with only two ports, an input port and an output port, like the network shown in Fig. 1. To characterize the performance of such a network, any of several parameter sets can be used, each of which has certain advantages.

Each parameter set is related to a set of four variables associated with the two-port model. Two of these variables represent the excitation of the network (independent variables), and the remaining two represent the response of the network to the excitation (dependent variables). If the network of Fig. 1 is excited by voltage sources V_1 and V_2, the network currents I_1 and I_2 will be related by the following equations (assuming the network behaves linearly):

$$I_1 = y_{11}V_1 + y_{12}V_2 \quad (1)$$

$$I_2 = y_{21}V_1 + y_{22}V_2 \quad (2)$$

In this case, with port voltages selected as independent variables and port currents taken as dependent variables, the relating parameters are called short-circuit admittance parameters, or y-parameters. In the absence of additional information, four measurements are required to determine the four parameters y_{11}, y_{21}, y_{12}, and y_{22}. Each measurement is made with one port of the network excited by a voltage source while the other port is short circuited. For example, y_{21}, the forward transadmittance, is the ratio of the current at port 2 to the voltage at port 1 with port 2 short circuited as shown in equation 3.

$$y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2 = 0} \text{ (output short circuited)} \quad (3)$$

If other independent and dependent variables had been chosen, the network would have been described, as before, by two linear equations similar to equations 1 and 2, except that the variables and the parameters describing their relationships would be different. However, all parameter sets contain the same information about a network, and it is always possible to calculate any set in terms of any other set.

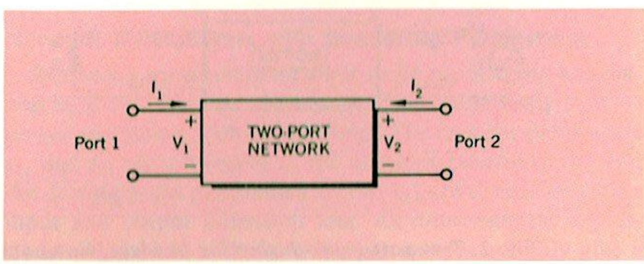


Fig. 1. *General two-port network.*

S-Parameters

The ease with which scattering parameters can be measured makes them especially well suited for describing transistors and other active devices. Measuring most other parameters calls for the input and output of the device to be successively opened and short circuited. This is difficult to do even at RF frequencies where lead inductance and capacitance make short and open circuits difficult to obtain. At higher frequencies these measurements typically require tuning stubs, separately adjusted at each measurement frequency, to reflect short or open circuit conditions to the device terminals. Not only is this inconvenient and tedious, but a tuning stub shunting the input or output may cause a transistor to oscillate, making the measurement difficult and invalid. S-parameters, on the other hand, are usually measured with the device imbedded between a 50Ω load and source, and there is very little chance for oscillations to occur.

Another important advantage of s-parameters stems from the fact that traveling waves, unlike terminal voltages and currents, do not vary in magnitude at points along a lossless transmission line. This means that scattering parameters can be measured on a device located at some distance from the measurement transducers, provided that the measuring device and the transducers are connected by low-loss transmission lines.

Generalized scattering parameters have been defined by K. Kurokawa.[1] These parameters describe the interrelationships of a new set of variables (a_i, b_i). The variables a_i and b_i are normalized complex voltage waves incident on and reflected from the i^{th} port of the network. They are defined in terms of the terminal voltage V_i, the terminal current I_i, and an arbitrary reference impedance Z_i, as follows

[1] K. Kurokawa, 'Power Waves and the Scattering Matrix,' IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-13, No. 2, March, 1965.

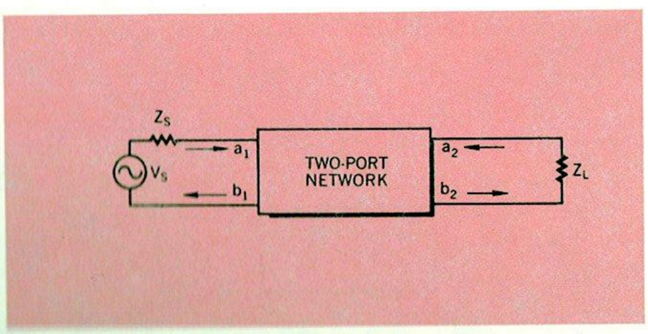


Fig. 2. Two-port network showing incident (a_1, a_2) and reflected (b_1, b_2) waves used in s-parameter definitions.

$$a_i = \frac{V_i + Z_i I_i}{2\sqrt{|\mathrm{Re}\, Z_i|}} \qquad (4)$$

$$b_i = \frac{V_i - Z_i^* I_i}{2\sqrt{|\mathrm{Re}\, Z_i|}} \qquad (5)$$

where the asterisk denotes the complex conjugate.

For most measurements and calculations it is convenient to assume that the reference impedance Z_i is positive and real. For the remainder of this article, then, all variables and parameters will be referenced to a single positive real impedance Z_o.

The wave functions used to define s-parameters for a two-port network are shown in Fig. 2. The independent variables a_1 and a_2 are normalized incident voltages, as follows:

$$a_1 = \frac{V_1 + I_1 Z_o}{2\sqrt{Z_o}} = \frac{\text{voltage wave incident on port 1}}{\sqrt{Z_o}} = \frac{V_{i1}}{\sqrt{Z_o}} \qquad (6)$$

$$a_2 = \frac{V_2 + I_2 Z_o}{2\sqrt{Z_o}} = \frac{\text{voltage wave incident on port 2}}{\sqrt{Z_o}} = \frac{V_{i2}}{\sqrt{Z_o}} \qquad (7)$$

Dependent variables b_1 and b_2 are normalized reflected voltages:

$$b_1 = \frac{V_1 - I_1 Z_o}{2\sqrt{Z_o}} = \frac{\text{voltage wave reflected (or emanating) from port 1}}{\sqrt{Z_o}} = \frac{V_{r1}}{\sqrt{Z_o}} \qquad (8)$$

$$b_2 = \frac{V_2 - I_2 Z_o}{2\sqrt{Z_o}} = \frac{\text{voltage wave reflected (or emanating) from port 2}}{\sqrt{Z_o}} = \frac{V_{r2}}{\sqrt{Z_o}} \qquad (9)$$

The linear equations describing the two-port network are then:

$$b_1 = s_{11} a_1 + s_{12} a_2 \qquad (10)$$

$$b_2 = s_{21} a_1 + s_{22} a_2 \qquad (11)$$

The s-parameters s_{11}, s_{22}, s_{21}, and s_{12} are:

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0} \qquad (12)$$

= Input reflection coefficient with the output port terminated by a matched load ($Z_L = Z_o$ sets $a_2 = 0$).

$$s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0} \qquad (13)$$

= Output reflection coefficient with the input terminated by a matched load ($Z_S = Z_o$ and $V_S = 0$).

$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0} = \text{Forward transmission (insertion) gain with the output port terminated in a matched load.} \quad (14)$$

$$s_{12} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0} = \text{Reverse transmission (insertion) gain with the input port terminated in a matched load.} \quad (15)$$

Notice that

$$s_{11} = \frac{b_1}{a_1} = \frac{\frac{V_1}{I_1} - Z_o}{\frac{V_1}{I_1} + Z_o} = \frac{Z_1 - Z_o}{Z_1 + Z_o} \quad (16)$$

and $$Z_1 = Z_o \frac{(1 + s_{11})}{(1 - s_{11})} \quad (17)$$

where $Z_1 = \frac{V_1}{I_1}$ is the input impedance at port 1.

This relationship between reflection coefficient and impedance is the basis of the Smith Chart transmission-line calculator. Consequently, the reflection coefficients s_{11} and s_{22} can be plotted on Smith charts, converted directly to impedance, and easily manipulated to determine matching networks for optimizing a circuit design.

The above equations show one of the important advantages of s-parameters, namely that they are simply gains and reflection coefficients, both familiar quantities to engineers. By comparison, some of the y-parameters described earlier in this article are not so familiar. For example, the y-parameter corresponding to insertion gain s_{21} is the 'forward transadmittance' y_{21} given by equation 3. Clearly, insertion gain gives by far the greater insight into the operation of the network.

Another advantage of s-parameters springs from the simple relationships between the variables a_1, a_2, b_1, and b_2, and various power waves:

$|a_1|^2$ = Power incident on the input of the network.
= Power available from a source of impedance Z_o.

$|a_2|^2$ = Power incident on the output of the network.
= Power reflected from the load.

$|b_1|^2$ = Power reflected from the input port of the network.
= Power available from a Z_o source minus the power delivered to the input of the network.

$|b_2|^2$ = Power reflected or emanating from the output of the network.
= Power incident on the load.
= Power that would be delivered to a Z_o load.

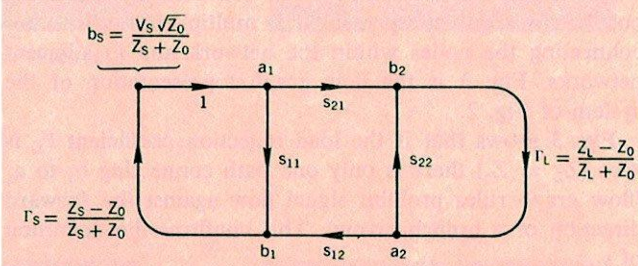


Fig. 3. *Flow graph of network of Fig. 2.*

Hence s-parameters are simply related to power gain and mismatch loss, quantities which are often of more interest than the corresponding voltage functions:

$$|s_{11}|^2 = \frac{\text{Power reflected from the network input}}{\text{Power incident on the network input}}$$

$$|s_{22}|^2 = \frac{\text{Power reflected from the network output}}{\text{Power incident on the network output}}$$

$$|s_{21}|^2 = \frac{\text{Power delivered to a } Z_o \text{ load}}{\text{Power available from } Z_o \text{ source}}$$

= Transducer power gain with Z_o load and source

$|s_{12}|^2$ = Reverse transducer power gain with Z_o load and source.

Network Calculations with Scattering Parameters

Scattering parameters turn out to be particularly convenient in many network calculations. This is especially true for power and power gain calculations. The transfer parameters s_{12} and s_{21} are a measure of the complex insertion gain, and the driving point parameters s_{11} and s_{22} are a measure of the input and output mismatch loss. As dimensionless expressions of gain and reflection, the parameters not only give a clear and meaningful physical interpretation of the network performance but also form a natural set of parameters for use with signal flow graphs[2,3]. Of course, it is not necessary to use signal flow graphs in order to use s-parameters, but flow graphs make s-parameter calculations extremely simple, and I recommend them very strongly. Flow graphs will be used in the examples that follow.

In a signal flow graph each port is represented by two nodes. Node a_n represents the wave coming into the device from another device at port n and node b_n represents the wave leaving the device at port n. The complex scattering coefficients are then represented as multipliers on branches connecting the nodes within the network and in adjacent networks. Fig. 3 is the flow graph representation of the system of Fig. 2.

Fig. 3 shows that if the load reflection coefficient Γ_L is zero ($Z_L = Z_o$) there is only one path connecting b_1 to a_1 (flow graph rules prohibit signal flow against the forward direction of a branch arrow). This confirms the definition of s_{11}:

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2 = \Gamma_L b_2 = 0}$$

The simplification of network analysis by flow graphs results from the application of the "non-touching loop rule." This rule applies a generalized formula to determine the transfer function between any two nodes within a complex system. The non-touching loop rule is explained in footnote 4.

[2] J. K. Hunton, 'Analysis of Microwave Measurement Techniques by Means of Signal Flow Graphs,' IRE Transactions on Microwave Theory and Techniques, Vol. MTT-8, No. 2, March, 1960.
[3] N. Kuhn, 'Simplified Signal Flow Graph Analysis,' Microwave Journal, Vol. 6, No. 11, Nov., 1963.

[4] The nontouching loop rule provides a simple method for writing the solution of any flow graph by inspection. The solution T (the ratio of the output variable to the input variable) is

$$T = \frac{\sum_k T_k \Delta_k}{\Delta}$$

where T_k = path gain of the k^{th} forward path

Δ = 1 − (sum of all individual loop gains) + (sum of the loop gain products of all possible combinations of two nontouching loops) − (sum of the loop gain products of all possible combinations of three nontouching loops) + ...

Δ_k = The value of Δ not touching the k_{th} forward path.

A path is a continuous succession of branches, and a forward path is a path connecting the input node to the output node, where no node is encountered more than once. Path gain is the product of all the branch multipliers along the path. A loop is a path which originates and terminates on the same node, no node being encountered more than once. Loop gain is the product of the branch multipliers around the loop.

For example, in Fig. 3 there is only one forward path from b_S to b_2 and its gain is s_{21}. There are two paths from b_S to b_1; their path gains are $s_{21}s_{12}\Gamma_L$ and s_{11} respectively. There are three individual loops, only one combination of two nontouching loops, and no combinations of three or more nontouching loops; therefore, the value of Δ for this network is

$$\Delta = 1 - (s_{11}\Gamma_S + s_{21}s_{12}\Gamma_L\Gamma_S + s_{22}\Gamma_L) + (s_{11}s_{22}\Gamma_L\Gamma_S).$$

The transfer function from b_S to b_2 is therefore

$$\frac{b_2}{b_S} = \frac{s_{21}}{\Delta}$$

Using scattering parameter flow-graphs and the non-touching loop rule, it is easy to calculate the transducer power gain with arbitrary load and source. In the following equations the load and source are described by their reflection coefficients Γ_L and Γ_S, respectively, referenced to the real characteristic impedance Z_o.

Transducer power gain

$$G_T = \frac{\text{Power delivered to the load}}{\text{Power available from the source}} = \frac{P_L}{P_{avS}}$$

$$P_L = P(\text{incident on load}) - P(\text{reflected from load})$$

$$= |b_2|^2 (1 - |\Gamma_L|^2)$$

$$P_{avS} = \frac{|b_S|^2}{(1 - |\Gamma_S|^2)}$$

$$G_T = \left|\frac{b_2}{b_S}\right|^2 (1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)$$

Using the non-touching loop rule,

$$\frac{b_2}{b_S} = \frac{s_{21}}{1 - s_{11}\Gamma_S - s_{22}\Gamma_L - s_{21}s_{12}\Gamma_L\Gamma_S + s_{11}\Gamma_S s_{22}\Gamma_L}$$

$$= \frac{s_{21}}{(1 - s_{11}\Gamma_S)(1 - s_{22}\Gamma_L) - s_{21}s_{12}\Gamma_L\Gamma_S}$$

$$G_T = \frac{|s_{21}|^2 (1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)}{|(1 - s_{11}\Gamma_S)(1 - s_{22}\Gamma_L) - s_{21}s_{12}\Gamma_L\Gamma_S|^2} \qquad (18)$$

Two other parameters of interest are:

1) Input reflection coefficient with the output termination arbitrary and $Z_S = Z_0$.

$$s'_{11} = \frac{b_1}{a_1} = \frac{s_{11}(1 - s_{22}\Gamma_L) + s_{21}s_{12}\Gamma_L}{1 - s_{22}\Gamma_L}$$

$$= s_{11} + \frac{s_{21}s_{12}\Gamma_L}{1 - s_{22}\Gamma_L} \qquad (19)$$

2) Voltage gain with arbitrary source and load impedances

$$A_V = \frac{V_2}{V_1} \qquad V_1 = (a_1 + b_1)\sqrt{Z_o} = V_{i1} + V_{r1}$$

$$V_2 = (a_2 + b_2)\sqrt{Z_o} = V_{i2} + V_{r2}$$

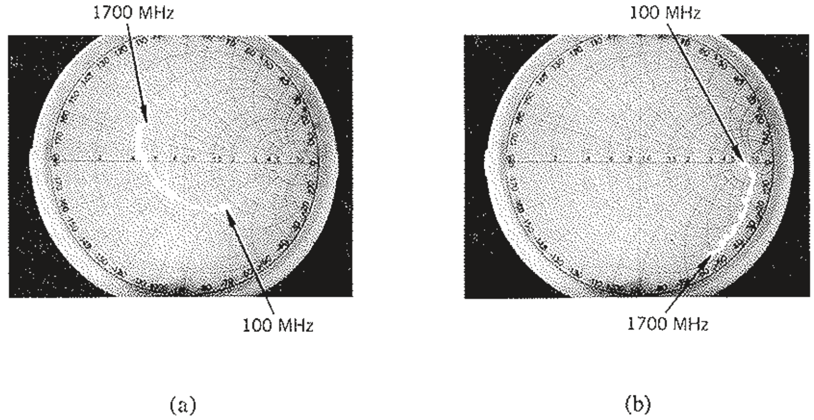
$$a_2 = \Gamma_L b_2$$

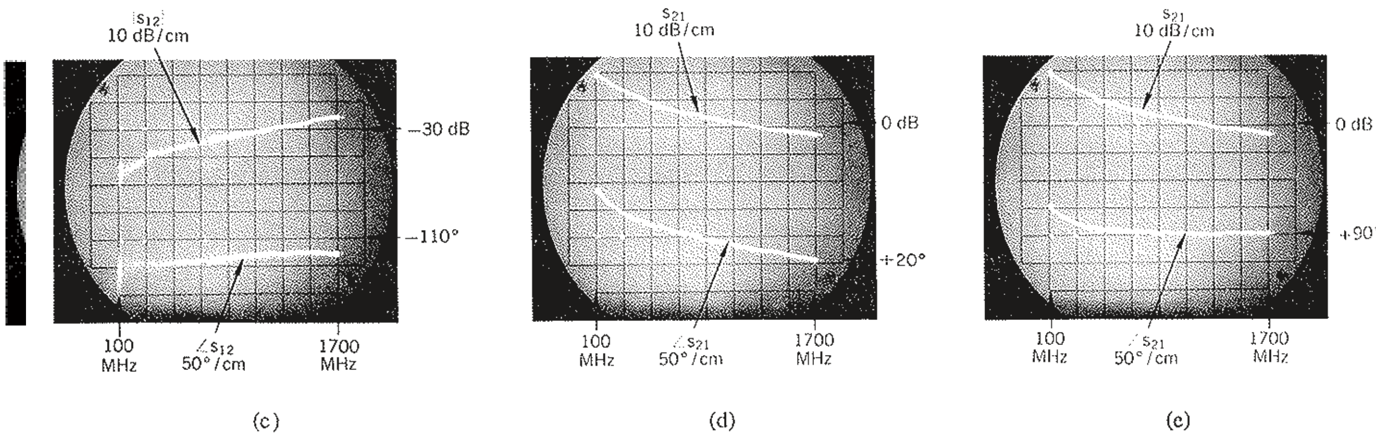
$$b_1 = s'_{11} a_1$$

$$A_V = \frac{b_2(1 + \Gamma_L)}{a_1(1 + s'_{11})} = \frac{s_{21}(1 + \Gamma_L)}{(1 - s_{22}\Gamma_L)(1 + s'_{11})} \qquad (20)$$

On p. 11 is a table of formulas for calculating many often-used network functions (power gains, driving point characteristics, etc.) in terms of scattering parameters. Also included in the table are conversion formulas between s-parameters and h-, y-, and z-parameters, which are other parameter sets used very often for specifying transistors at

Fig. 4. *S parameters of 2N3478 transistor in common-emitter configuration, measured by -hp- Model 8410A Network Analyzer.* (a) s_{11}. *Outermost circle on Smith Chart overlay corresponds to* $|s_{11}| = 1$. (b) s_{22}. *Scale factor same as* (a). (c) s_{12}. (d) s_{21}. (e) s_{21} *with line stretcher adjusted to remove linear phase shift above 500 MHz.*





lower frequencies. Two important figures of merit used for comparing transistors, f_t and f_{max}, are also given, and their relationship to s-parameters is indicated.

Amplifier Design Using Scattering Parameters

The remainder of this article will show by several examples how s-parameters are used in the design of transistor amplifiers and oscillators. To keep the discussion from becoming bogged down in extraneous details, the emphasis in these examples will be on s-parameter design *methods*, and mathematical manipulations will be omitted wherever possible.

Measurement of S-Parameters

Most design problems will begin with a tentative selection of a device and the measurement of its s-parameters. Fig. 4 is a set of oscillograms containing complete s-parameter data for a 2N3478 transistor in the common-emitter configuration. These oscillograms are the results of swept-frequency measurements made with the new microwave network analyzer described elsewhere in this issue. They represent the actual s-parameters of this transistor between 100 MHz and 1700 MHz.

In Fig. 5, the magnitude of s_{21} from Fig. 4(d) is replotted on a logarithmic frequency scale, along with additional data on s_{21} below 100 MHz, measured with a vector voltmeter. The magnitude of s_{21} is essentially constant to 125 MHz, and then rolls off at a slope of 6 dB/octave. The phase angle of s_{21}, as seen in Fig. 4(d), varies linearly with frequency above about 500 MHz. By adjusting a calibrated line stretcher in the network analyzer, a compensating linear phase shift was introduced, and the phase curve of Fig. 4(e) resulted. To go from the phase curve of Fig. 4(d) to that of Fig. 4(e) required 3.35 cm of line, equivalent to a pure time delay of 112 picoseconds.

After removal of the constant-delay, or linear-phase, component, the phase angle of s_{21} for this transistor [Fig. 4(e)] varies from 180° at dc to +90° at high frequencies, passing through +135° at 125 MHz, the −3 dB point of the magnitude curve. In other words, s_{21} behaves like a single pole in the frequency domain, and it is possible to write a closed expression for it. This expression is

$$s_{21} = \frac{-s_{21_0} e^{-j\omega T_0}}{1 + j\frac{\omega}{\omega_0}} \qquad (21)$$

where

$$T_0 = 112 \text{ ps}$$
$$\omega = 2\pi f$$
$$\omega_0 = 2\pi \times 125 \text{ MHz}$$
$$s_{21_0} = 11.2 = 21 \text{ dB}$$

The time delay $T_0 = 112$ ps is due primarily to the transit time of minority carriers (electrons) across the base of this npn transistor.

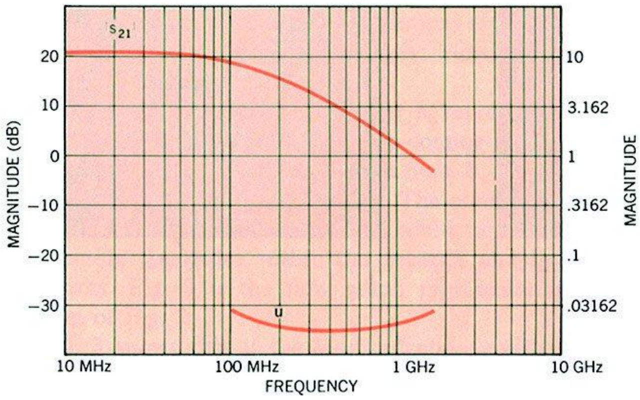


Fig. 5. *Top curve:* $|s_{21}|$ *from Fig. 4 replotted on logarithmic frequency scale. Data below 100 MHz measured with -hp- 8405A Vector Voltmeter. Bottom curve: unilateral figure of merit, calculated from s parameters (see text).*

Narrow-Band Amplifier Design

Suppose now that this 2N3478 transistor is to be used in a simple amplifier, operating between a 50Ω source and a 50Ω load, and optimized for power gain at 300 MHz by means of lossless input and output matching networks. Since reverse gain s_{12} for this transistor is quite small — 50 dB smaller than forward gain s_{21}, according to Fig. 4 — there is a possibility that it can be neglected. If this is so, the design problem will be much simpler, because setting s_{12} equal to zero will make the design equations much less complicated.

In determining how much error will be introduced by assuming $s_{12} = 0$, the first step is to calculate the unilateral figure of merit u, using the formula given in the table on p. 11, i.e.

$$u = \frac{|s_{11}s_{12}s_{21}s_{22}|}{|(1 - |s_{11}|^2)(1 - |s_{22}|^2)|} \quad . \qquad (22)$$

A plot of u as a function of frequency, calculated from the measured parameters, appears in Fig. 5. Now if G_{Tu} is the transducer power gain with $s_{12} = 0$ and G_T is the actual transducer power gain, the maximum error introduced by using G_{Tu} instead of G_T is given by the following relationship:

$$\frac{1}{(1+u)^2} < \frac{G_T}{G_{Tu}} < \frac{1}{(1-u)^2} \quad . \qquad (23)$$

From Fig. 5, the maximum value of u is about 0.03, so the maximum error in this case turns out to be about ±0.25 dB at 100 MHz. This is small enough to justify the assumption that $s_{12} = 0$.

Incidentally, a small reverse gain, or feedback factor, s_{12}, is an important and desirable property for a transistor to have, for reasons other than that it simplifies amplifier design. A small feedback factor means that the input characteristics of the completed amplifier will be independent of the load, and the output will be independent of the source impedance. In most amplifiers, isolation of source and load is an important consideration.

Returning now to the amplifier design, the unilateral expression for transducer power gain, obtained either by setting $s_{12} = 0$ in equation 18 or by looking in the table on p. 11, is

$$G_{Tu} = \frac{|s_{21}|^2(1 - |\Gamma_s|^2)(1 - |\Gamma_L|^2)}{|1 - s_{11}\Gamma_s|^2|1 - s_{22}\Gamma_L|^2} \quad . \qquad (24)$$

When $|s_{11}|$ and $|s_{22}|$ are both less than one, as they are in this case, maximum G_{Tu} occurs for $\Gamma_S = s^*_{11}$ and $\Gamma_L = s^*_{22}$ (table, p. 11).

The next step in the design is to synthesize matching networks which will transform the 50Ω load and source impedances to the impedances corresponding to reflection coefficients of s^*_{11} and s^*_{22}, respectively. Since this is to be a single-frequency amplifier, the matching networks need not be complicated. Simple series-capacitor, shunt-inductor networks will not only do the job, but will also provide a handy means of biasing the transistor — via the inductor — and of isolating the dc bias from the load and source.

Values of L and C to be used in the matching networks are determined using the Smith Chart of Fig. 6. First, points corresponding to s_{11}, s^*_{11}, s_{22}, and s^*_{22} at 300 MHz are plotted. Each point represents the tip of a vector leading away from the center of the chart, its length equal to the magnitude of the reflection coefficient being plotted, and its angle equal to the phase of the coefficient. Next, a combination of constant-resistance and constant-conductance circles is found, leading from the center of the chart, representing 50Ω, to s^*_{11} and s^*_{22}. The circles on the Smith Chart are constant-resistance circles; increasing series capacitive reactance moves an impedance point counter-clockwise along these circles. In this case, the circle to be used for finding series C is the one passing through the center of the chart, as shown by the solid line in Fig. 6.

Increasing shunt inductive susceptance moves impedance points clockwise along constant-conductance circles. These circles are like the constant-resistance circles, but they are on another Smith Chart, this one being just the reverse of the one in Fig. 6. The constant-conductance circles for shunt L all pass through the leftmost point of the chart rather than the rightmost point. The circles to be used are those passing through s^*_{11} and s^*_{22}, as shown by the dashed lines in Fig. 6.

Once these circles have been located, the normalized values of L and C needed for the matching networks are calculated from readings taken from the reactance and susceptance scales of the Smith Charts. Each element's reactance or susceptance is the difference between the scale readings at the two end points of a circular arc. Which arc corresponds to which element is indicated in Fig. 6. The final network and the element values, normalized and unnormalized, are shown in Fig. 7.

Broadband Amplifier Design

Designing a broadband amplifier, that is, one which has nearly constant gain over a prescribed frequency range, is a matter of surrounding a transistor with external elements in order to compensate for the variation of forward gain $|s_{21}|$ with frequency. This can be done in either of two ways — first, negative feedback, or second, selective mismatching of the input and output circuitry. We will use the second method. When feedback is used, it is usually convenient to convert to y- or z-parameters (for shunt or series feedback respectively) using the conversion equations given in the table, p. 12, and a digital computer.

Equation 24 for the unilateral transducer power gain can be factored into three parts:

$$G_{Tu} = G_o G_1 G_2$$

where

$$G_o = |s_{21}|^2$$

$$G_1 = \frac{1 - |\Gamma_s|^2}{|1 - s_{11}\Gamma_s|^2}$$

$$G_2 = \frac{1 - |\Gamma_L|^2}{|1 - s_{22}\Gamma_L|^2}.$$

When a broadband amplifier is designed by selective mismatching, the gain contributions of G_1 and G_2 are varied to compensate for the variations of $G_o = |s_{21}|^2$ with frequency.

Suppose that the 2N3478 transistor whose s-parameters are given in Fig. 4 is to be used in a broadband amplifier which has a constant gain of 10 dB over a frequency range of 300 MHz to 700 MHz. The amplifier is to be driven from a 50Ω source and is to drive a 50Ω load. According to Fig. 5,

$$|s_{21}|^2 = 13 \text{ dB at } 300 \text{ MHz}$$
$$= 10 \text{ dB at } 450 \text{ MHz}$$
$$= 6 \text{ dB at } 700 \text{ MHz}.$$

To realize an amplifier with a constant gain of 10 dB, source and load matching networks must be found which will decrease the gain by 3 dB at 300 MHz, leave the gain the same at 450 MHz, and increase the gain by 4 dB at 700 MHz.

Although in the general case both a source matching network and a load matching network would be designed, $G_{1\,max}$ (i.e., G_1 for $\Gamma_S = s^*_{11}$) for this transistor is less than 1 dB over the frequencies of interest, which means there is little to be gained by matching the source. Consequently, for this example, only a load-matching network will be designed. Procedures for designing source-matching networks are identical to those used for designing load-matching networks.

The first step in the design is to plot s^*_{22} over the required frequency range on the Smith Chart, Fig. 8. Next, a set of constant-gain circles is drawn. Each circle is drawn for a single frequency; its center is on a line between the center of the Smith Chart and the point representing s^*_{22} at that frequency. The distance from the center of the Smith Chart to the center of the constant gain circle is given by (these equations also appear in the table, p. 11):

$$r_2 = \frac{g_2|s_{22}|}{1 - |s_{22}|^2(1 - g_2)}$$

where

$$g_2 = \frac{G_2}{G_{2\,max}} = G_2(1 - |s_{22}|^2).$$

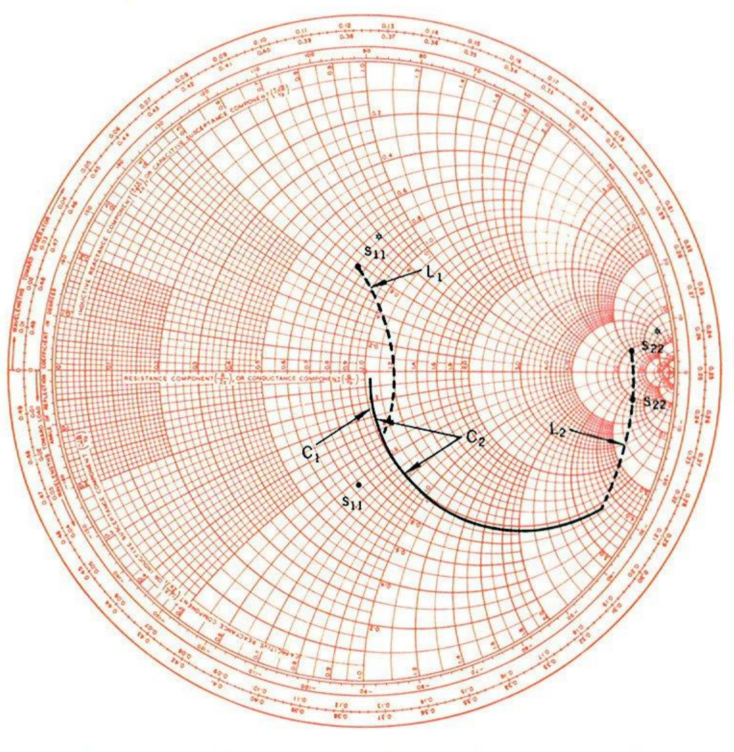


Fig. 6. *Smith Chart for 300-MHz amplifier design example.*

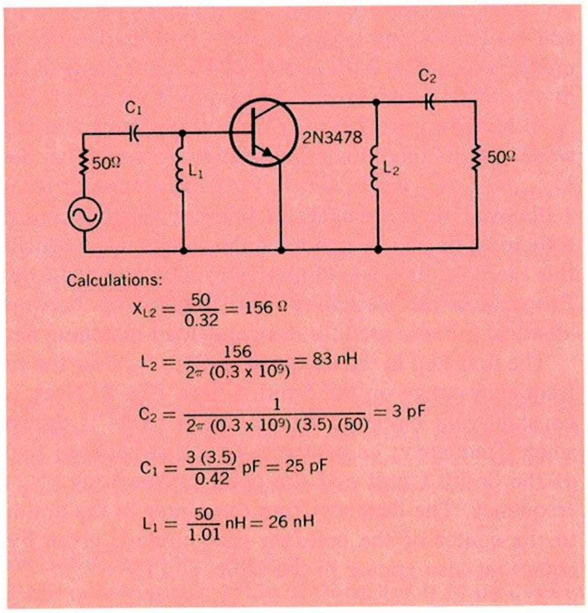


Fig. 7. *300-MHz amplifier with matching networks for maximum power gain.*

The radius of the constant-gain circle is

$$\rho_2 = \frac{\sqrt{1 - g_2}\,(1 - |s_{22}|^2)}{1 - |s_{22}|^2\,(1 - g_2)}.$$

For this example, three circles will be drawn, one for $G_2 = -3$ dB at 300 MHz, one for $G_2 = 0$ dB at 450 MHz, and one for $G_2 = +4$ dB at 700 MHz. Since $|s_{22}|$ for this transistor is constant at 0.85 over the frequency range [see Fig. 4(b)], $G_{2\,max}$ for all three circles is $(0.278)^{-1}$, or 5.6 dB. The three constant-gain circles are indicated in Fig. 8.

The required matching network must transform the center of the Smith Chart, representing 50Ω, to some point on the −3 dB circle at 300 MHz, to some point on the 0 dB circle at 450 MHz, and to some point on the +4 dB circle at 700 MHz. There are undoubtedly many networks that will do this. One which is satisfactory is a combination of two inductors, one in shunt and one in series, as shown in Fig. 9.

Shunt and series elements move impedance points on the Smith Chart along constant-conductance and constant-resistance circles, as I explained in the narrow-band design example which preceded this broadband example. The shunt inductance transforms the 50Ω load along a circle of constant conductance and varying (with frequency) inductive susceptance. The series inductor transforms the combination of the 50Ω load and the shunt inductance along circles of constant resistance and varying inductive reactance.

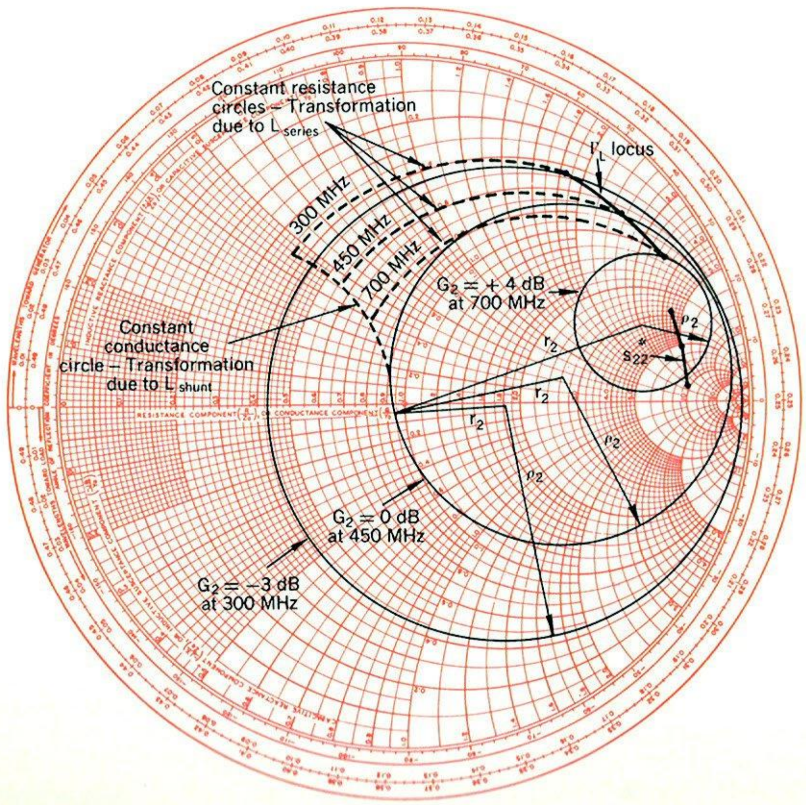


Fig. 8. *Smith Chart for broadband amplifier design example.*

Optimizing the values of shunt and series L is a cut-and-try process to adjust these elements so that

- —the transformed load reflection terminates on the right gain circle at each frequency, and
- —the susceptance component decreases with frequency and the reactance component increases with frequency. (This rule applies to inductors; capacitors would behave in the opposite way.)

Once appropriate constant-conductance and constant-resistance circles have been found, the reactances and susceptances of the elements can be read directly from the Smith Chart. Then the element values are calculated, the same as they were for the narrow-band design.

Fig. 10 is a schematic diagram of the completed broadband amplifier, with unnormalized element values.

Stability Considerations and the Design of Reflection Amplifiers and Oscillators

When the real part of the input impedance of a network is negative, the corresponding input reflection coefficient (equation 17) is greater than one, and the network can be used as the basis for two important types of circuits, reflection amplifiers and oscillators. A reflection amplifier (Fig. 11) can be realized with a circulator—a nonreciprocal three-port device — and a negative-resistance device. The circulator is used to separate the incident (input) wave from the larger wave reflected by the negative-resistance device. Theoretically, if the circulator is perfect and has a positive real characteristic impedance Z_o, an amplifier with infinite gain can be built by selecting a negative-resistance device whose input impedance has a real part equal to $-Z_o$ and an imaginary part equal to zero (the imaginary part can be set equal to zero by tuning, if necessary).

Amplifiers, of course, are not supposed to oscillate, whether they are reflection amplifiers or some other kind. There is a convenient criterion based upon scattering parameters for determining whether a device is stable or potentially unstable with given source and load impedances. Referring again to the flow graph of Fig. 3, the ratio of the reflected voltage wave b_1 to the input voltage wave b_S is

$$\frac{b_1}{b_S} = \frac{s'_{11}}{1 - \Gamma_S s'_{11}}$$

where s'_{11} is the input reflection coefficient with $\Gamma_S = 0$ (that is, $Z_S = Z_o$) and an arbitrary load impedance Z_L, as defined in equation 19.

If at some frequency

$$\Gamma_S s'_{11} = 1 \qquad (25)$$

the circuit is unstable and will oscillate at that frequency. On the other hand, if

$$|s'_{11}| < \left|\frac{1}{\Gamma_S}\right|$$

the device is unconditionally stable and will not oscillate, whatever the phase angle of Γ_S might be.

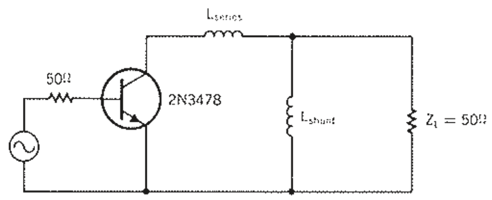


Fig. 9. *Combination of shunt and series inductances is suitable matching network for broadband amplifier.*

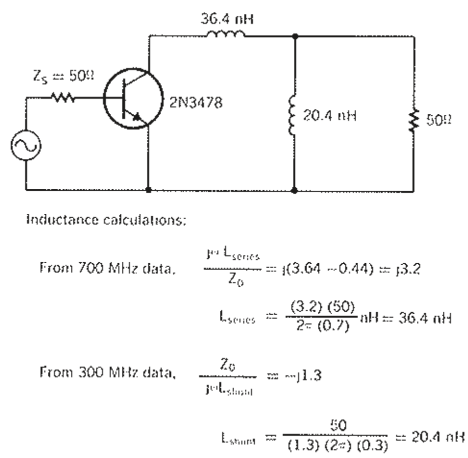


Fig. 10. *Broadband amplifier with constant gain of 10 dB from 300 MHz to 700 MHz.*

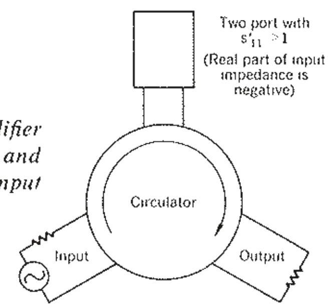


Fig. 11. *Reflection amplifier consists of circulator and transistor with negative input resistance.*

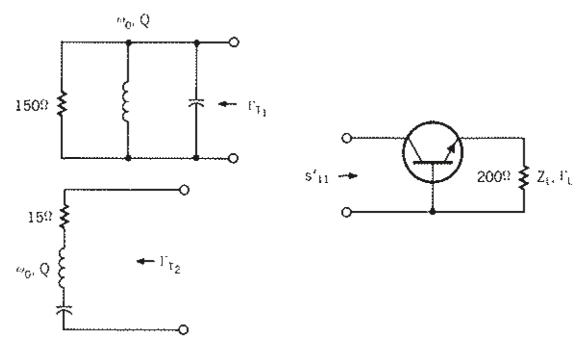


Fig. 12. *Transistor oscillator is designed by choosing tank circuit such that* $\Gamma_T s'_{11} = 1$.

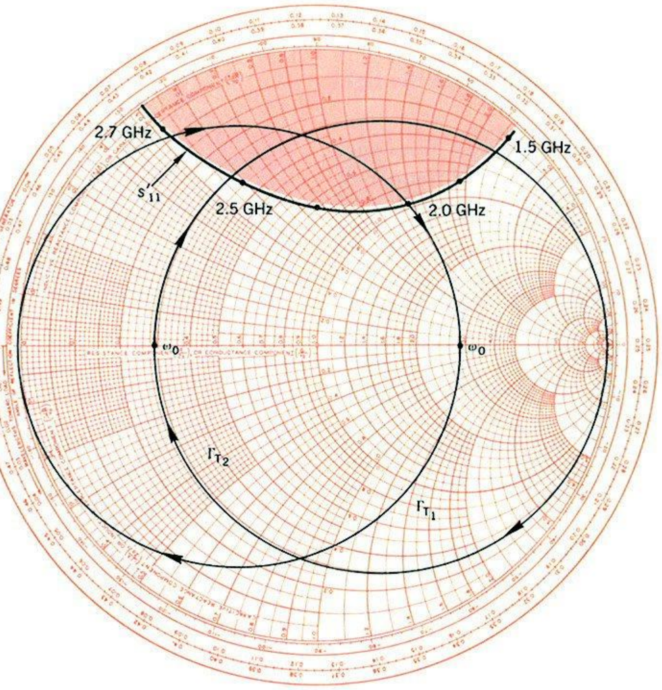


Fig. 13. *Smith Chart for transistor oscillator design example.*

As an example of how these principles of stability are applied in design problems, consider the transistor oscillator design illustrated in Fig. 12. In this case the input reflection coefficient s'_{11} is the reflection coefficient looking into the collector circuit, and the 'source' reflection coefficient Γ_S is one of the two tank-circuit reflection coefficients, Γ_{T1} or Γ_{T2}. From equation 19,

$$s'_{11} = s_{11} + \frac{s_{12}\, s_{21}\, \Gamma_L}{1 - s_{22}\, \Gamma_L}$$

To make the transistor oscillate, s'_{11} and Γ_S must be adjusted so that they satisfy equation 25. There are four steps in the design procedure:

—Measure the four scattering parameters of the transistor as functions of frequency.

—Choose a load reflection coefficient Γ_L which makes s'_{11} greater than unity. In general, it may also take an external feedback element which increases $s_{12}\, s_{21}$ to make s'_{11} greater than one.

—Plot $1/s'_{11}$ on a Smith Chart. (If the new network analyzer is being used to measure the s-parameters of the transistor, $1/s'_{11}$ can be measured directly by reversing the reference and test channel connections between the reflection test unit and the harmonic frequency converter. The polar display with a Smith Chart overlay will then give the desired plot immediately.)

—Connect either the series or the parallel tank circuit to the collector circuit and tune it so that Γ_{T1} or Γ_{T2} is large enough to satisfy equation 25 (the tank circuit reflection coefficient plays the role of Γ_S in this equation).

Fig. 13 shows a Smith Chart plot of $1/s'_{11}$ for a high-frequency transistor in the common-base configuration. Load impedance Z_L is 200Ω, which means that Γ_L referred to 50Ω is 0.6. Reflection coefficients Γ_{T1} and Γ_{T2} are also plotted as functions of the resonant frequencies of the two tank circuits. Oscillations occur when the locus of Γ_{T1} or Γ_{T2} passes through the shaded region. Thus this transistor would oscillate from 1.5 to 2.5 GHz with a series tuned circuit and from 2.0 to 2.7 GHz with a parallel tuned circuit.

—*Richard W. Anderson*

Additional Reading on S-Parameters

Besides the papers referenced in the footnotes of the article, the following articles and books contain information on s-parameter design procedures and flow graphs.

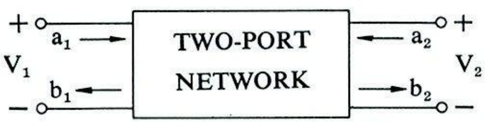
—F. Weinert, 'Scattering Parameters Speed Design of High-Frequency Transistor Circuits,' Electronics, Vol. 39, No. 18, Sept. 5, 1966.

—G. Fredricks, 'How to Use S-Parameters for Transistor Circuit Design,' EEE, Vol. 14, No. 12, Dec., 1966.

—D. C. Youla, 'On Scattering Matrices Normalized to Complex Port Numbers,' Proc. IRE, Vol. 49, No. 7, July, 1961.

—J. G. Linvill and J. F. Gibbons, 'Transistors and Active Circuits,' McGraw-Hill, 1961. (No s-parameters, but good treatment of Smith Chart design methods.)

Useful Scattering Parameter Relationships



$$b_1 = s_{11}a_1 + s_{12}a_2$$

$$b_2 = s_{21}a_1 + s_{22}a_2$$

Input reflection coefficient with arbitrary Z_L

$$s'_{11} = s_{11} + \frac{s_{12}s_{21}\Gamma_L}{1 - s_{22}\Gamma_L}$$

Output reflection coefficient with arbitrary Z_S

$$s'_{22} = s_{22} + \frac{s_{12}s_{21}\Gamma_S}{1 - s_{11}\Gamma_S}$$

Voltage gain with arbitrary Z_L and Z_S

$$A_V = \frac{V_2}{V_1} = \frac{s_{21}(1 + \Gamma_L)}{(1 - s_{22}\Gamma_L)(1 + s'_{11})}$$

$$\text{Power Gain} = \frac{\text{Power delivered to load}}{\text{Power input to network}}$$

$$G = \frac{|s_{21}|^2(1 - |\Gamma_L|^2)}{(1 - |s_{11}|^2) + |\Gamma_L|^2(|s_{22}|^2 - |D|^2) - 2\,\text{Re}(\Gamma_L N)}$$

$$\text{Available Power Gain} = \frac{\text{Power available from network}}{\text{Power available from source}}$$

$$G_A = \frac{|s_{21}|^2(1 - |\Gamma_S|^2)}{(1 - |s_{22}|^2) + |\Gamma_S|^2(|s_{11}|^2 - |D|^2) - 2\,\text{Re}(\Gamma_S M)}$$

$$\text{Transducer Power Gain} = \frac{\text{Power delivered to load}}{\text{Power available from source}}$$

$$G_T = \frac{|s_{21}|^2(1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)}{|(1 - s_{11}\Gamma_S)(1 - s_{22}\Gamma_L) - s_{12}s_{21}\Gamma_L\Gamma_S|^2}$$

Unilateral Transducer Power Gain ($s_{12} = 0$)

$$G_{Tu} = \frac{|s_{21}|^2(1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)}{|1 - s_{11}\Gamma_S|^2\,|1 - s_{22}\Gamma_L|^2}$$

$$= G_o G_1 G_2$$

$$G_o = |s_{21}|^2$$

$$G_1 = \frac{1 - |\Gamma_S|^2}{|1 - s_{11}\Gamma_S|^2}$$

$$G_2 = \frac{1 - |\Gamma_L|^2}{|1 - s_{22}\Gamma_L|^2}$$

Maximum Unilateral Transducer Power Gain when $|s_{11}| < 1$ and $|s_{22}| < 1$

$$G_u = \frac{|s_{21}|^2}{|(1 - |s_{11}|^2)(1 - |s_{22}|)^2|}$$

$$= G_o\, G_{1\,max}\, G_{2\,max}$$

$$G_{i\,max} = \frac{1}{1 - |s_{ii}|^2} \qquad i = 1, 2$$

This maximum attained for $\Gamma_S = s^*_{11}$ and $\Gamma_L = s^*_{22}$

Constant Gain Circles (Unilateral case: $s_{12} = 0$)

—center of constant gain circle is on line between center of Smith Chart and point representing s^*_{ii}

—distance of center of circle from center of Smith Chart:

$$r_i = \frac{g_i|s_{ii}|}{1 - |s_{ii}|^2(1 - g_i)}$$

—radius of circle:

$$\rho_i = \frac{\sqrt{1 - g_i}\,(1 - |s_{ii}|^2)}{1 - |s_{ii}|^2(1 - g_i)}$$

where: $i = 1, 2$

$$\text{and } g_i = \frac{G_i}{G_{i\,max}} = G_i(1 - |s_{ii}|^2)$$

Unilateral Figure of Merit

$$u = \frac{|s_{11}s_{22}s_{12}s_{21}|}{|(1 - |s_{11}|^2)(1 - |s_{22}|^2)|}$$

Error Limits on Unilateral Gain Calculation

$$\frac{1}{(1 + u^2)} < \frac{G_T}{G_{Tu}} < \frac{1}{(1 - u^2)}$$

Conditions for Absolute Stability

No passive source or load will cause network to oscillate if a, b, and c are all satisfied.

a. $|s_{11}| < 1, |s_{22}| < 1$

b. $\left| \dfrac{|s_{12}s_{21}| - |M^*|}{|s_{11}|^2 - |D|^2} \right| > 1$

c. $\left| \dfrac{|s_{12}s_{21}| - |N^*|}{|s_{22}|^2 - |D|^2} \right| > 1$

Condition that a two-port network can be simultaneously matched with a positive real source and load:

$K > 1$ or $C < 1$

$C =$ Linvill C factor

Linvill C Factor

$$C = K^{-1}$$

$$K = \frac{1 + |D|^2 - |s_{11}|^2 - |s_{22}|^2}{2\,|s_{12}s_{21}|}$$

Source and Load for Simultaneous Match

$$\Gamma_{mS} = M^* \left[\frac{B_1 \pm \sqrt{B_1^2 - 4\,|M|^2}}{2\,|M|^2} \right]$$

$$\Gamma_{mL} = N^* \left[\frac{B_2 \pm \sqrt{B_2^2 - 4\,|N|^2}}{2\,|N|^2} \right]$$

Where $B_1 = 1 + |s_{11}|^2 - |s_{22}|^2 - |D|^2$

$B_2 = 1 + |s_{22}|^2 - |s_{11}|^2 - |D|^2$

Maximum Available Power Gain

If $K > 1$,

$$G_{A\,max} = \left| \frac{s_{21}}{s_{12}} (K \pm \sqrt{K^2 - 1}) \right|$$

$K = C^{-1}$

$C =$ Linvill C Factor

(Use minus sign when B_1 is positive, plus sign when B_1 is negative. For definition of B_1 see 'Source and Load for Simultaneous Match,' elsewhere in this table.)

$$D = s_{11}s_{22} - s_{12}s_{21}$$

$$M = s_{11} - D\,s^*_{22}$$

$$N = s_{22} - D\,s^*_{11}$$

s-parameters in terms of h-, y-, and z-parameters	h-, y-, and z-parameters in terms of s-parameters
$s_{11} = \dfrac{(z_{11} - 1)(z_{22} + 1) - z_{12}z_{21}}{(z_{11} + 1)(z_{22} + 1) - z_{12}z_{21}}$	$z_{11} = \dfrac{(1 + s_{11})(1 - s_{22}) + s_{12}s_{21}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}}$
$s_{12} = \dfrac{2z_{12}}{(z_{11} + 1)(z_{22} + 1) - z_{12}z_{21}}$	$z_{12} = \dfrac{2s_{12}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}}$
$s_{21} = \dfrac{2z_{21}}{(z_{11} + 1)(z_{22} + 1) - z_{12}z_{21}}$	$z_{21} = \dfrac{2s_{21}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}}$
$s_{22} = \dfrac{(z_{11} + 1)(z_{22} - 1) - z_{12}z_{21}}{(z_{11} + 1)(z_{22} + 1) - z_{12}z_{21}}$	$z_{22} = \dfrac{(1 + s_{22})(1 - s_{11}) + s_{12}s_{21}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}}$
$s_{11} = \dfrac{(1 - y_{11})(1 + y_{22}) + y_{12}y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{11} = \dfrac{(1 + s_{22})(1 - s_{11}) + s_{12}s_{21}}{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}}$
$s_{12} = \dfrac{-2y_{12}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{12} = \dfrac{-2s_{12}}{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}}$
$s_{21} = \dfrac{-2y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{21} = \dfrac{-2s_{21}}{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}}$
$s_{22} = \dfrac{(1 + y_{11})(1 - y_{22}) + y_{12}y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$	$y_{22} = \dfrac{(1 + s_{11})(1 - s_{22}) + s_{12}s_{21}}{(1 + s_{22})(1 + s_{11}) - s_{12}s_{21}}$
$s_{11} = \dfrac{(h_{11} - 1)(h_{22} + 1) - h_{12}h_{21}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{11} = \dfrac{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}}{(1 - s_{11})(1 + s_{22}) + s_{12}s_{21}}$
$s_{12} = \dfrac{2h_{12}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{12} = \dfrac{2s_{12}}{(1 - s_{11})(1 + s_{22}) + s_{12}s_{21}}$
$s_{21} = \dfrac{-2h_{21}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{21} = \dfrac{-2s_{21}}{(1 - s_{11})(1 + s_{22}) + s_{12}s_{21}}$
$s_{22} = \dfrac{(1 + h_{11})(1 - h_{22}) + h_{12}h_{21}}{(h_{11} + 1)(h_{22} + 1) - h_{12}h_{21}}$	$h_{22} = \dfrac{(1 - s_{22})(1 - s_{11}) - s_{12}s_{21}}{(1 - s_{11})(1 + s_{22}) + s_{12}s_{21}}$

The h-, y-, and z-parameters listed above are all normalized to Z_o. If h′, y′, and z′ are the actual parameters, then		
$z_{11}' = z_{11}Z_o$	$y_{11}' = \dfrac{y_{11}}{Z_o}$	$h_{11}' = h_{11}Z_o$
$z_{12}' = z_{12}Z_o$	$y_{12}' = \dfrac{y_{12}}{Z_o}$	$h_{12}' = h_{12}$
$z_{21}' = z_{21}Z_o$	$y_{21}' = \dfrac{y_{21}}{Z_o}$	$h_{21}' = h_{21}$
$z_{22}' = z_{22}Z_o$	$y_{22}' = \dfrac{y_{22}}{Z_o}$	$h_{22}' = \dfrac{h_{22}}{Z_o}$

Reprinted Compliments of
Hewlett-Packard Journal
Vol. 18, No. 6 FEB 1967

Fig. 1. *Automatic Network Analyzer for measuring complex impedances, gain, loss, and phase shift from 0.11 to 12.4 GHz consists of (l. to r.), Model 8411A Harmonic Frequency Converter, Model 8410A Main Frame, and a plug-in display module (either Model 8413A Phase-Gain Indicator or Model 8414A Polar Display). Network Analyzer makes swept or single-frequency measurements. See Fig. 8 for other system components.*

An Advanced New Network Analyzer for Sweep-Measuring Amplitude and Phase from 0.1 to 12.4 GHz

The information obtainable with a new network analyzer greatly improves microwave design practices, especially where phase information is important.

A NEW MICROWAVE NETWORK ANALYZER developed in the -hp- microwave laboratory promises to be of major importance in many electronic fields, especially those concerned with the phase properties of microwave systems and components. The new instrument sweep-measures the magnitude and phase of reflection and transmission coefficients over the range from 110 MHz to 12.4 GHz. This makes it possible for the analyzer to completely characterize active and passive devices, since nearly every parameter of interest for high-frequency devices can be measured including gain, attenuation, phase, impedance, admittance and others.

The new analyzer represents a major step in the continuing trend to automation in microwave measurements, a trend recognized in several articles in this publication and elsewhere*. Systems that are especially aided by the kinds of automated measurements the analyzer makes are the modern systems that emphasize phase properties, such as electronically-scanned radar and monopulse and doppler radar. Similarly, optimum use of the new high-frequency solid-state devices that make systems such as phased-array radars economically practical is dependent on sophisticated measurements. The reason for this de-

* See references on page 9.

-hp- Journal readers:

We believe you who work with frequencies above 100 MHz will be especially interested in this issue because it discusses an important new system that measures gain, phase, impedance, admittance and attenuation on a swept basis *from 110 MHz to 12.4 GHz. In other words the system will measure all network parameters not only of passive networks and devices but also of transistors and even of negative real impedances. Readout is on a meter or on a scope which presents measured performance over a whole frequency band at a glance.*

The new system leads to wider use of the familiar quantities we usually call reflection and transmission coefficients. These coefficients are also known as 'scattering parameters', and using them in combination with the new system leads to more sophisticated design techniques including computerized design. An informative article about scattering parameters begins on p. 13.

Obviously, the new system is a powerful tool for the engineer. In addition, it has important implications for the whole microwave engineering field in the future. This is also discussed in this issue (p. 11) by Paul Ely, engineering manager of our microwave laboratory.

I invite your attention to what we believe is unusually important microwave information.

Sincerely, Editor

pendence is that these solid-state devices can best be utilized in new functions if they can be completely characterized and understood.

The analyzer characterizes networks by measuring their complex small-signal parameters. The particular types of parameters measured are called the scattering or "s" parameters. These parameters have proved a valuable tool for the design engineer because of their inherent ease of measurement, their design advantages and the intuitive insight they provide. A separate article in this issue deals with their theory and describes new design practices developed with them at Hewlett-Packard.

Network Analyzer Concept

The concept of the network analyzer follows naturally from network-parameter theory. Measuring s-parameters is a matter of measuring (a) the ratio of the magnitudes and (b) the relative phase angles of response and excitation signals at the ports of a network with the other ports terminated in a specified 'characteristic' or reference impedance. It is not difficult to define the basic elements of a network analyzer system to perform these measurements (Fig. 3). First, a source of excitation is required. Then a transducer instrument is needed to convert the excitation signal and the response signals produced by the unknown to a set of output signals containing the network information (a dual-directional coupler for measuring the complex reflection coefficient s_{11} is illustrated). Next, an instrument capable of measuring magnitude ratio and phase difference is used to extract the pertinent information from the test signals. A readout mechanism to present the data completes the basic network analyzer.

The above is the concept that has been followed in designing the new network analyzer. A further refinement of the concept is the use of a plug-in readout. Although the network parameter data are the same for each application (i.e., magnitude and phase), the form in which the data are most useful depends upon the application.

Table I System Components

MODEL	FUNCTION	RANGE
8410A Network Analyzer Main Frame	Mainframe for readout modules, includes tuning circuits, IF amplifiers, and precision IF attenuator.	0.11 to 12.4 GHz when used with Model 8411A.
8411A Harmonic Frequency Converter	Converts 2 RF input signals 0.11 to 12.4 GHz into 20-MHz IF signals.	0.11 to 12.4 GHz when used with the 8410A. Impedance 50 ohms.
8413A Phase-Gain Indicator	Plug-in module for 8410A Mainframe provides meter display of relative amplitude and phase between input signals, auxiliary outputs for scope or X-Y recorder.	Full scale ±3, 10, 30 dB and ±6, 18, 60, 180 degrees. Auxiliary outputs 50 mV/dB and 10 mV/degree.
8414A Polar Display Unit	Plug-in module for 8410A Mainframe. CRT polar display of amplitude and phase. X-Y outputs for high resolution polar and Smith Chart impedance plots.	Internal graticule CRT for nonparallax viewing. Amplitude calibration in five linear steps. Phase in 10° intervals through 360°. Smith Chart overlays for direct impedance readout (normalized to 50 ohms).
8740A Transmission Test Unit	Simplifies RF input and test device connection for attenuation or gain test. Accepts RF input signal from source and splits into reference and test channels for connection to 8411A and the unknown device. Calibrated line stretcher balances out linear phase shift when test device is inserted.	0.11 to 12.4 GHz. Impedance 50 ohms.
8741A Reflection Test Unit	Wide-band reflectometer, phase balanced for swept or spot frequency impedance tests below 2 GHz. Accepts RF input and provides connections for unknown test device and 8411A. Movable reference plane.	0.11 to 2.0 GHz.
8742A Reflection Test Unit	Ultra-wide band reflectometer, phase balanced for impedance tests above 2.0 GHz. Movable reference plane.	2.0 to 12.4 GHz

Fig. 2. *Typical test setup using new Network Analyzer (top center) to sweep-measure transmission of microwave filter. Magnitude and phase are measured on Analyzer meter and presented as a function of frequency on oscilloscope. Magnitude and phase can also be presented in polar form on a Polar Display scope which plugs in, in place of Phase Gain Indicator and will feed external recorder.*

Other pieces of auxiliary equipment will, in general, be added to complete a specific measurement. Examples would be bias supplies for active devices and matched loads for termination purposes.

Here then is a very flexible system that defines completely the complex parameters of an active or passive network. It provides this information, much of which was previously very difficult or prohibitively expensive to obtain, over a huge frequency range with an ease and rapidity that consistently intrigues those who see it the first time. Specific features of the network analyzer are the following:

1. One system measures both magnitude and phase of all network parameters from 110 MHz to 12.4 GHz. The measurements can be made at a single frequency or on a swept frequency basis over octave bandwidths.
2. The analyzer combines wide dynamic range with high measurement resolution. Direct dynamic display range is 60 dB in magnitude and 360° of phase. Precise internal attenuators and a calibrated phase offset allow expanded measurements with better than 0.1 dB resolution in magnitude and 0.1° in phase.
3. It is accurate. Precision components are used throughout to assure basic accuracy. The two-channel comparative technique removes error terms caused by the source and variations common to both channels.
4. A choice of display allows the data to be presented in the most useful form for the specific measurement. The measured data are also provided in analog form for external oscilloscope, recorder, or digital display.

Frequency Translation by Sampling

Figs. 1 and 8 show the elements of the analyzer system and Table I lists the elements, their functions, and their frequency ranges. The basic analyzer (Fig. 1) consists of three units: a main frame, either of two plug-in display modules, and a harmonic frequency converter. The transducer instruments for reflection and transmission (Fig. 8) complete the system.

The key technique that allows the new microwave network analyzer to measure complex ratio is the technique of frequency translation by sampling. The block diagram of the basic analyzer shown in Fig. 4 is helpful to understand this technique. Sampling as used in this system is a special case of heterodyning, which translates the input signals to a lower, fixed IF frequency where normal circuitry can be used to measure amplitude and phase relationships. The principle is to exchange the local oscillator of a conventional heterodyne system with a pulse generator which generates a train of very narrow pulses. If each pulse within the train is narrow compared to a period of the applied RF signal, the sampler becomes a harmonic mixer with equal efficiency for each harmonic. Thus sampling-type mixing has the advantage that a single system can operate over an extremely wide input frequency range. In the case of the network analyzer this range is 110 MHz to 12.4 GHz.

In order to make the system capable of swept frequency operation, an internal phase-lock loop keeps one channel of the two-channel network analyzer tuned to the incoming signal. Tuning of the phase-lock loop is entirely automatic. When the loop is unlocked, it automatically tunes back and forth across a portion of whatever octave-wide frequency band has been selected by the user. When any harmonic of the tracking-oscillator frequency falls 20 MHz below the input frequency, i.e., when $f_{in} - nf_{osc} = 20$ MHz, the loop stops searching and locks. Search and lock-on are normally completed in

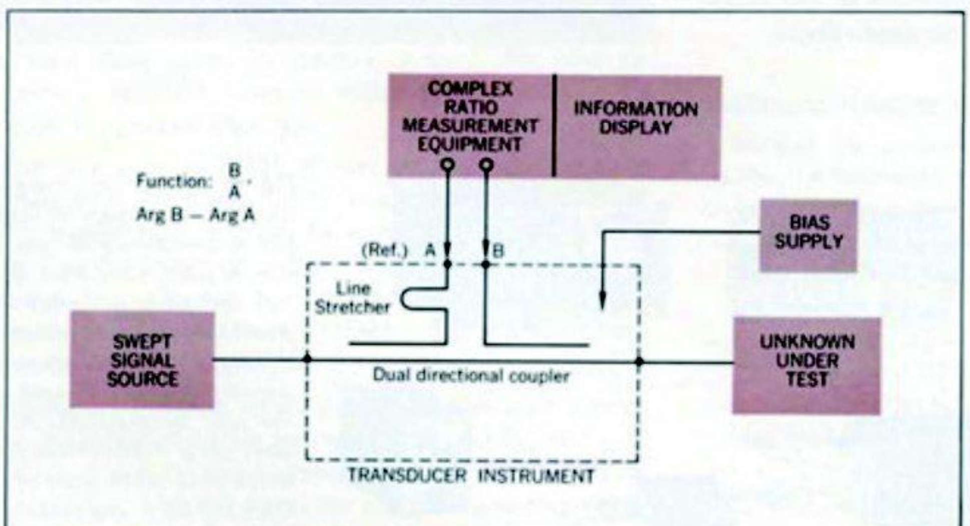


Fig. 3. Network Analyzer concept follows from network theory, as explained in text.

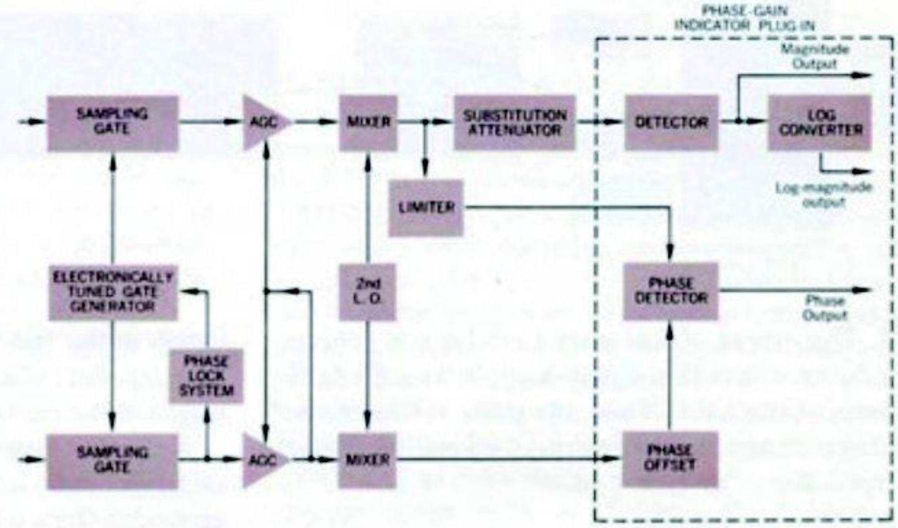


Fig. 4. *Basic system used in Analyzer to achieve frequency translation by a sampling technique.*

about 20 μs. The loop will remain locked for sweep rates as high as 220 GHz/sec (a rate corresponding to about 30 sweeps per second over the highest frequency band, 8 to 12.4 GHz).

The IF signals reconstructed from the sampler outputs are both 20-MHz signals, but since frequency conversion is a linear process, these signals have the same relative amplitudes and phases as the microwave reference and test signals. Thus gain and phase information are preserved, and all signal processing and measurements take place at a constant frequency.

Referring again to Fig. 4, the IF signals are first applied to a pair of matched AGC (automatic gain control) amplifiers. The AGC amplifiers perform two functions: they keep the signal level in the reference channel constant, and they vary the gain in the test channel so that the test signal level does not change when variations common to both channels occur. This action is equivalent to taking a ratio and removes the effects of power variations in the signal source, of frequency response characteristics common to both channels, and of similar common-mode variations.

Before the signals are sent to the display unit, a second frequency conversion from 20 MHz to 278 kHz is performed. To obtain the desired dB and degree quantities, the phase-gain indicator plug-in display unit (Fig. 4) contains a linear phase detector and an analog logarithmic converter which is accurate over a 60 dB range of test signal amplitudes. Ratio (in dB) and relative phase can be read on the meter of the display unit if desired, but the plug-in also provides calibrated dc-coupled voltages proportional to gain (as a linear ratio or in dB) and phase for display on the vertical channels of an oscilloscope or X-Y recorder. If the horizontal input to the oscilloscope or recorder is a voltage proportional to frequency, the complete amplitude and phase response of the test device can be displayed.

Polar Display Unit

The Polar Display Unit (Fig. 5) converts polar quantities of magnitude and phase into a form suitable for display on a CRT. This is accomplished by using two balanced-modulator phase detectors. The phase of the test channel is shifted 90° with respect to the reference channel before being applied to the balanced modulator. The output of one modulator is proportional to A sin θ. This signal is amplified and fed to the vertical plates of

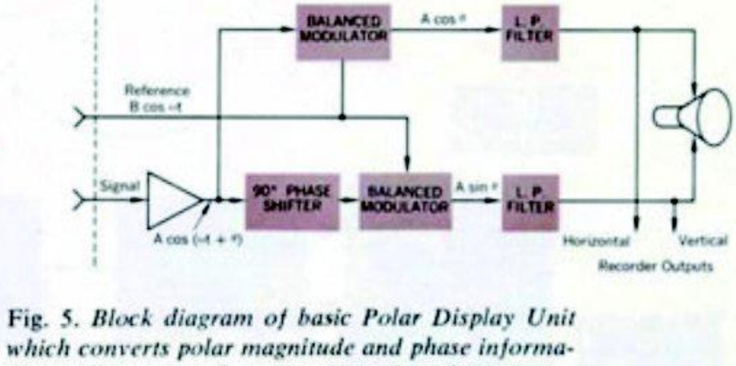


Fig. 5. *Block diagram of basic Polar Display Unit which converts polar magnitude and phase information to be presented on its self-contained CRT.*

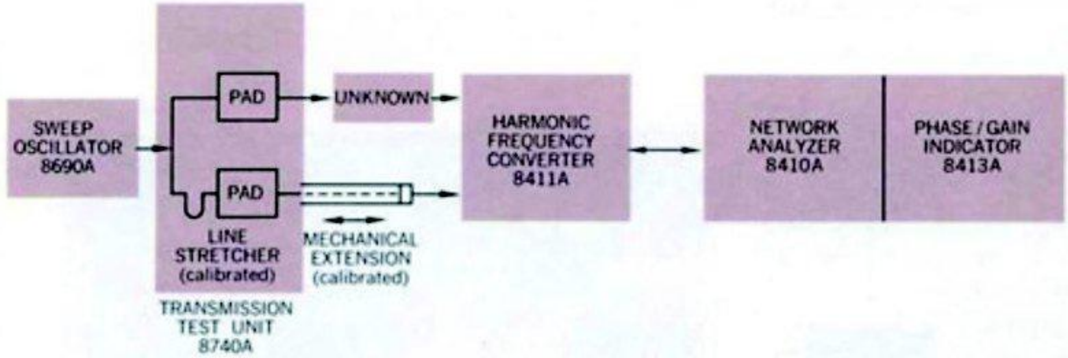


Fig. 6. *Block diagram of transmission test with new Network Analyzer. S-parameters s_{12} and s_{21} can be measured thus.*

the CRT. The output of the other modulator is proportional to A cos θ and this signal is applied to the horizontal plates of the CRT. Thus, the polar vector can be displayed in rectangular coordinates of an oscilloscope or an X-Y recorder.

Transmission Measurements

Fig. 6 illustrates the measurement of the transmission coefficients s_{21} and s_{12} with the network analyzer. As explained on p. 13, these parameters are the forward and reverse transmission gain of the network when the output and input ports, respectively, are terminated in the reference or characteristic impedances. Transmission measurements are used to determine bandwidth, gain, insertion loss, resonances, group delay, phase shift and distortion, etc. For these measurements a swept-frequency source provides an input to the transmission test unit, which consists of a power divider, a line stretcher and two fixed attenuators. The transmission test unit has two outputs, a reference channel and a test channel, which track each other closely in amplitude and phase from dc to 12.4 GHz. The device to be measured is inserted in the test channel, as shown in Fig. 6. Variations in the physical length of test devices can be compensated for by a mechanical extension of the reference channel of the test unit. Thus the magnitude and phase of the transmission coefficient is measured with respect to a length of precision air-line. Of course gain- and phase-difference measurements between similar devices can also be made by inserting a device in each channel. Excess electrical length in the test device can be compensated for by the line stretcher which acts as an extension to the electrical length of the reference channel.

Since the impedance levels in both reference and test channels are 50 ohms, the ratio of the voltage magnitudes applied to the test and reference channels of the harmonic frequency converter is proportional to the insertion gain (or loss), s_{12} or s_{21}, of the device with respect to the reference impedance 50 ohms. The phase between these voltages is likewise the insertion phase shift. When insertion parameters are being measured, the quantities of greatest interest are a logarithmic measure of gain (dB) and transfer phase shift. To obtain these quantities, the network analyzer is used with the phase-gain indicator plug-in.

Reflection Measurements

Complex reflection coefficient, admittance, and impedance measurements are made using the set-up shown in Fig. 7. In this case the signal from the swept-frequency source drives a reflection test unit consisting of a dual directional coupler and a line stretcher. Only two reflection test units are needed to cover the analyzer's entire frequency range — one for frequencies between 0.11 and 2.0 GHz, and one for frequencies from 2.0 to 12.4 GHz.

For reflection measurements, the polar display plug-in with its built-in internal-graticule (parallax-free) CRT is most convenient. A Smith chart overlay for this display converts reflection coefficients directly to impedance or

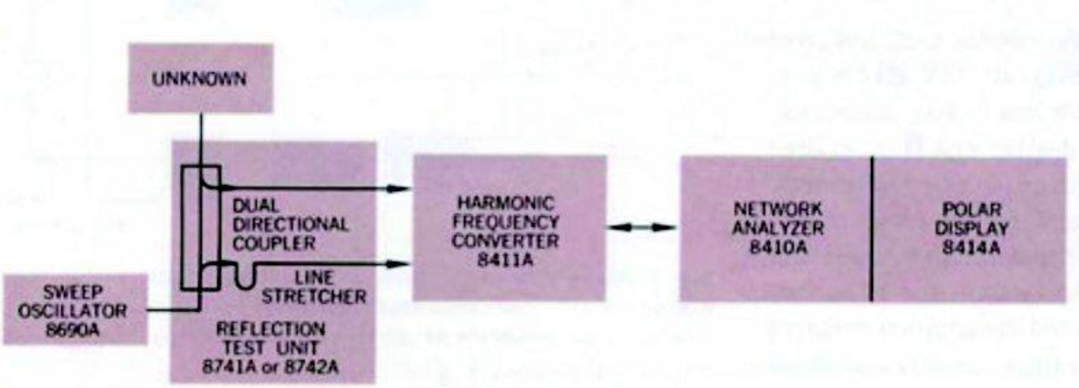


Fig. 7. *Block diagram of reflection (impedance) test with new Network Analyzer.*

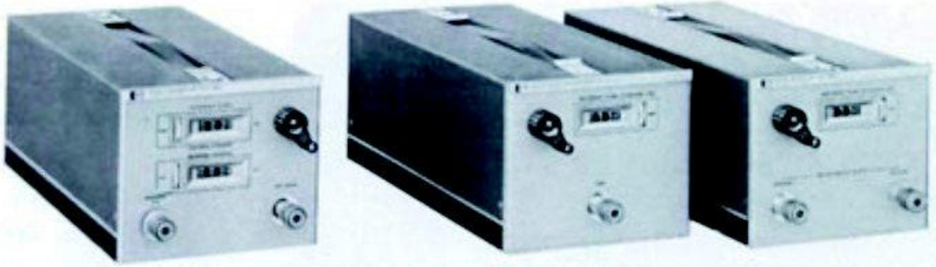


Fig. 8. *Model 8740A Transmission Test Unit or Models 8741A and 8742A Reflection Test Units contain the calibrated line stretchers, attenuators, and directional couplers needed for network analysis.*

admittance. The line stretchers within the test units allow *the plane at which the measurement is made to be extended past the connector to the unknown device*. Thus the Smith Chart display can reveal the impedance or admittance within the test device as frequency is varied without the necessity of graphical manipulations of data plotted on a Smith chart. Seeing the impedance locus of a device over an octave-wide frequency range plotted on this display and watching it change as a tuning adjustment or some other condition is varied is truly an impressive experience for anyone who has ever had to use older methods.

Design considerations

In designing the new analyzer and in achieving some of its performance characteristics, several interesting circuit innovations were devised. Space limitations preclude a detailed treatment, but a summary of some of the salient innovations is given below.

a. A wide-band phase-lock loop was designed to enable the system to sweep rapidly. Maximum sweep rate, which is determined by the loop bandwidth, is about 220 GHz per second.

b. A voltage-controlled oscillator was devised to permit the harmonic frequency converter to tune over more than an octave in frequency (Fig. 9). With the varactors in Fig. 9 connected to the emitters, the voltage swings are small, permitting a low dc bias voltage to be used to get a large value of capacitance. Since the oscillator period is proportional to the varactor capacitance, a large tuning range results.

c. The fast voltage-step needed to obtain fast sampling in the harmonic frequency converter is initiated in a step-recovery diode that operates in a 25-ohm line. To obtain a step of adequate voltage to accommodate the external sampled signal, it is necessary to drive this diode with substantial current. The current is provided by the basic power amplifier shown in Fig. 10. The amplifier follows the local oscillator and consists of emitter followers in a binary tree configuration. Each of the four output transistors supplies nearly 200 mA peak-to-peak over the range from 60 to 150 MHz.

d. In the IF circuits of the signal and reference channels of the main part of the analyzer, AGC action is required but with small relative amplitude and phase change between channels. To achieve this, AGC amplifiers were devised which remove up to 20 dB of power variation while giving less than 1 dB of differential amplitude change and less than about 2° of differential phase change. AGC action is obtained from the current-dependent incremental impedance characteristic of a silicon diode.

e. Amplitude and phase change in the phase/gain in-

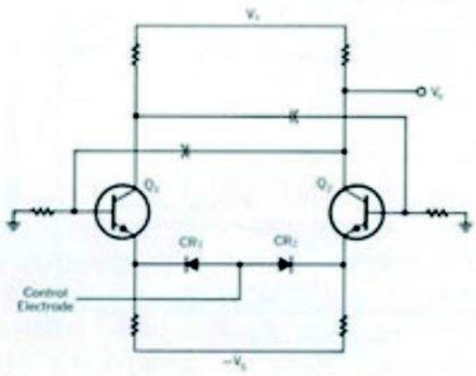


Fig. 9. *Emitter-coupled multivibrator is used for voltage-controlled local oscillator. Tuning range is 60–150 MHz.*

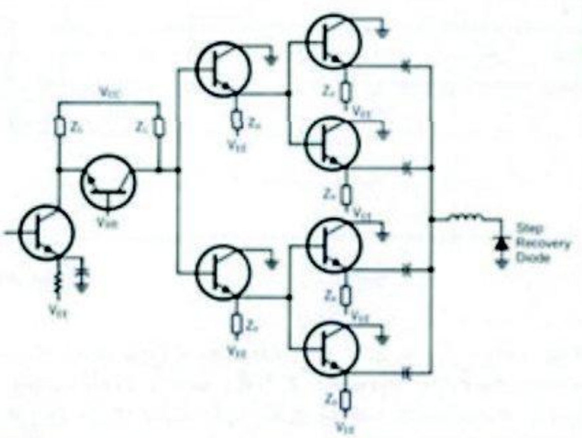


Fig. 10. *Wide-band power amplifier provides at least 0.75 amp p-p over frequency range of 60–150 MHz.*

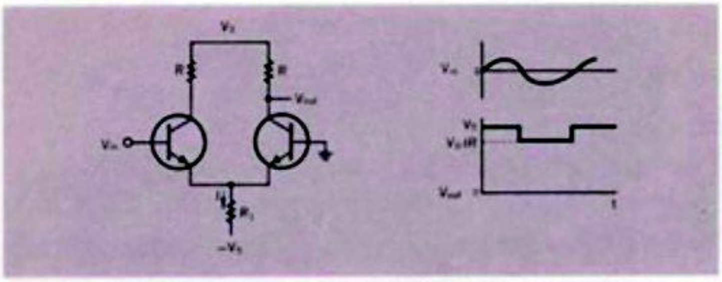
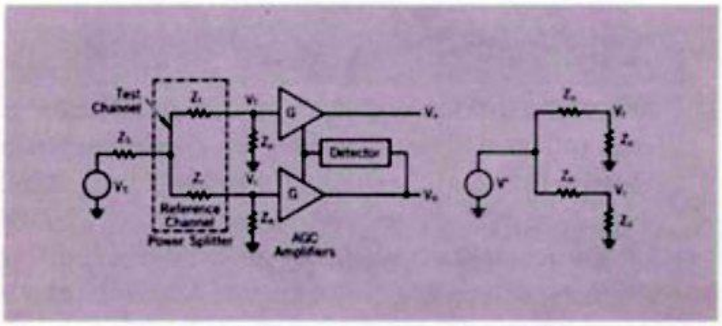
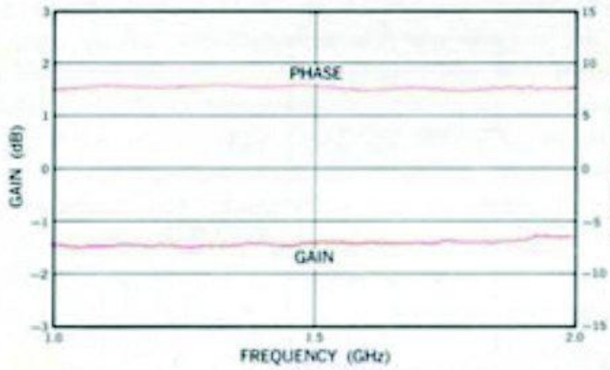


Fig. 11. *Limiting amplifier with two transistors switching total current I. Output voltage is dependent only on V_s and R.*

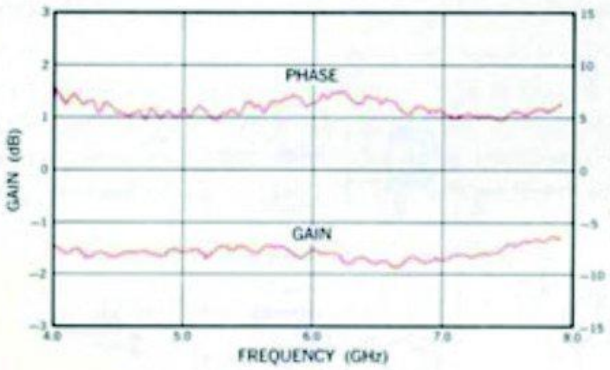


(a) *(b)*

Fig. 12(a). *Equivalent configuration of power divider and AGC amplifiers for calculating ratio.* 12(b). *Simplified equivalent with resultant zero-impedance source V′.*



(a)



(b)

Fig. 13(a). *Phase and gain responses typical of Network Analyzer between 1 GHz and 2 GHz: Analyzer is accurate within ±0.1 dB and 1.0° in swept measurements. Accuracy in single-frequency measurements is better.* (b). *Phase and gain responses typical of Network Analyzer between 4 GHz and 8 GHz.*

dicator unit were reduced by using a series of limiters of the type shown in Fig. 11. To prevent added delay when the amplifier starts to limit, the transistors are cut off but not allowed to saturate. A single limiter exhibits less than 1° of phase shift when passing from linear operation to limiting. Output voltage is dependent only on V_s and R.

f. A major engineering contribution occurred in the form of two wide-band directional couplers used in the reflection test units. The couplers have 30 to 40 dB of directivity over their frequency ranges of 0.1 to 2 GHz and 2 to 12.4 GHz. This represents a combination of performance characteristics heretofore unattainable.

g. Normally, a power divider operates with its three ports matched. In the transmission test unit a precision power divider was devised which operates with the source port matched but with the output ports mismatched. The ratio calculation performed by the AGC amplifiers (Fig. 12a) has the effect of making V′ a low-impedance source, so that the two channels do not interact with each other. If Z_t and Z_r in Fig. 12(b) are made equal to Z_o, standing waves are not present.

Performance

Typical measurement accuracies for the 1-to-2-GHz frequency range are shown in Fig. 13(a) which is a plot of the network analyzer's amplitude and phase responses over this range. Gain and phase measurements accurate within ±0.1 dB and ±1° appear reasonable for swept measurements. For single-frequency measurements, the accuracy is much better — comparable to that of standards-laboratory instruments.

Fig. 13(b) shows the amplitude and phase responses of the analyzer from 4 GHz to 8 GHz. The slightly-reduced calibration accuracy apparent in Fig. 13(b) can be attributed principally to the increased reflection coefficient of the harmonic frequency converter (wideband sampler) at higher frequencies.

Phase errors caused by changes in the amplitude of the signal in the test channel are shown in Fig. 14. Greatest accuracy in phase measurements is obtained for signal levels within ±20 dB of mid-range. In this range, phase ambiguities are less than ±1°.

Fig. 15 shows the gain and phase stability of the network analyzer. Over a period of six hours, total drift did not exceed 0.05 dB and 0.2° under normal room-temperature variations.

Gain and phase accuracies at low signal levels are limited by the signal-to-noise ratio at the output of the harmonic frequency converter. Noise in the test channel is below −80 dBm, which means that accurate measurements can be made for test-channel amplitudes down to −70 dBm or less.

More typical measured data are presented in the s-parameter article (p. 13).

Acknowledgments

It is a pleasure to acknowledge the contributions of the following members of the Microwave Division.

Network Analyzer Main Frame:
Kenneth S. Conroy, George M. Courreges, Wayne A. Fleming, Robert W. Pace.

Harmonic Frequency Converter:
William J. Benham, Richard T. Lee.

Phase/Gain Indicator Unit:
Donald G. Ferney, David R. Gildea, Alan L. Seely.

Polar Display Unit:
Larry L. Ritchie, William A. Rytand.

Transmission and Reflection Test Units:
Jean Pierre Castric, Wilmot B. Hunter, George R. Kirkpatrick, Richard A. Lyons, Auber G. Ryals.

Industrial Design:
Ned R. Kuypers.

We also wish to thank Microwave Division engineering manager Paul C. Ely, Jr. for his encouragement and helpful suggestions.

—Richard W. Anderson and Orthell T. Dennison

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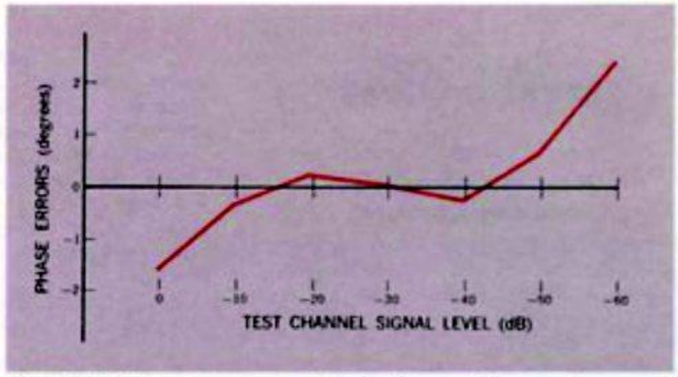

Fig. 14. *Phase errors caused by changes in amplitude of signal in test channel are typically very small. Ambiguity is less than ±1° for signals within ±20 dB of mid-range.*

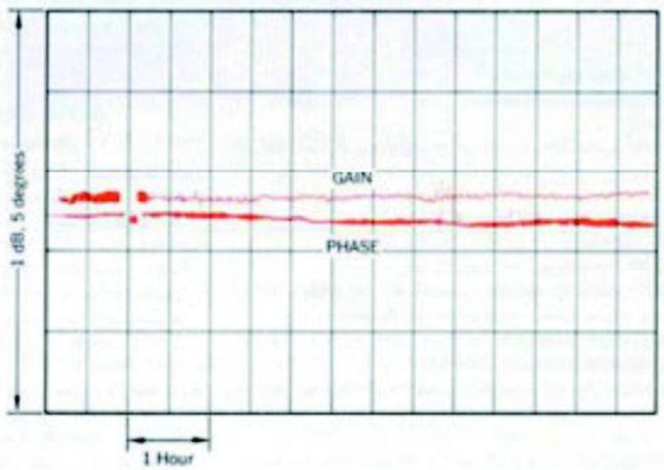

Fig. 15. *Typical gain and phase stability of Network Analyzer. Total drift under normal room-temperature variations over six-hour period was <0.05 dB and <0.2°.*

Richard W. Anderson

Dick Anderson joined the -hp- Microwave Division in 1959 after receiving his BSEE degree from Utah State University. He has contributed to the development of a variety of microwave instruments and devices, and he is now manager of the network analyzers section of the -hp- Microwave Laboratory. In 1963 he received his MS degree in electrical engineering from Stanford University on the -hp- Honors Cooperative Program.

Dick is active in the IEEE Group on Microwave Theory and Techniques. He holds several patents and has published a number of technical papers, his most recent being 'Sampler Based Instruments for Complex Signal and Network Analysis,' presented at WESCON 1966.

Orthell T. Dennison

Ted Dennison joined the -hp- Microwave Laboratory in 1960. He contributed to the design of the 415C and 415D SWR Meters, and directed the development of the 416B Ratio Meter and the later stages of the development of the 690-series Sweep Oscillators. Since 1963 he has been project leader of the 8410A Network Analyzer program.

Ted received his BSEE degree in 1960 from Utah State University and his MSEE degree in 1964 from the University of Santa Clara. At Santa Clara, he specialized in control systems and solid-state design. Ted is a member of IEEE, Sigma Tau, and Phi Kappa Phi.