Everything You Wanted To Know About Microwave Things, But Not So Much You'd Have To Get Too Familiar With James Clerk Maxwell

This paper will deal with a variety of microwave information that is not contained on most data sheets. It involves things like cable attenuation, power handling capability, etc.

First off, an information tidbit. One of our microwave tools that has not been completely superseded by the electronic calculator is a cardboard sliderule called the HP Reflectometer Calculator, (Lit # 5952-0948). It relates SWR to reflection coefficient to return loss and mismatch loss. It shows you mismatch losses for power measurements when you know the SWR of the source and the SWR of the power sensor. And it is a handy reminder for the numerical vs. the dB ratios of voltage and power.

ATTENUATION AND VOLTAGE AND POWER RATINGS OF MICROWAVE THINGS

HP sells a variety of accessories that are basically unspecified. These are the connector adapters, cables, etc. A typical customer question might ask for the attenuation of the RG-214/U cable used in the HP 11500A Cable Assembly. The answer is to look in the Reference Data Book For Radio Engineers. Cable attenuation is plotted for all sorts of coaxial cables from the RG-59/U video cable we use with BNC connectors to large 3 1/8-inch rigid coax, which we don't sell. Incidentally, our HP 11500A which is 6-feet long would have attenuation of 2.4 dB at 10 GHz (40 dB per 100 feet).

The ITT tables on the Army-Navy list of preferred Radio-Frequency cables also shows other useful data. For example, the capacitance of RG-59/U cable is 21.5 pF per foot. This may be useful if you need to know the shunt loading capacitance of some BNC video cable which may connect a microwave detector to the input jack of your oscilloscope, if you want to use it unterminated, and look at the pulsed RF envelope.

Those same tables show that the minimum operating voltage of the RG-214/U cable is 5,000 volts rms. In a 50 system, that might imply that you could put one half megawatt on the cable. But there are two things that limit that power. The Type-N connector on each end is only rated at 500 volts and if you look at one, you can see why. It uses air dielectric while the cable itself uses polyethylene dielectric. That connector rating of 500 volts, of course, permits about 5000 watts. But if you consider the attenuation of the cable, that will limit your CW power to much less. Consider the 2.4 dB at X-Band. That means that about 7 feet of the cable would exhibit 3 dB or a loss of half the power. I'd guess that dissipating even 100 watts in 7 feet of cable would be a problem. Think of it as bottling up the heat of a 100 watt light bulb in that length of cable. If you figured that the 7 foot cable could dissipate 50 watts on a continuous basis, then at X-band with its 3 dB of loss, the cable could transmit about 100 watts CW. So you have to use that sort of analysis to figure power. At lower frequencies, of course, the losses are far less.

Generally, cables can carry up to the connector limit in peak pulsed power; for example, the 5 kW through the connector, and then use a duty cycle that limited the average power to an acceptable amount. Of course, this whole analysis explains why the big transmitting stations use the large rigid coax of 3 1/8 inch or even 6 inch diameter for their CW signals.

In analyzing peak-power-carrying capacity, you need also to consider the standing wave effects on a line. The real world would seldom have a perfectly matched load and a flat transmission line. For example, suppose that a peak pulse in a line hits an antenna with an SWR of 1.5. That means that a reverse wave of power 14 dB below the incident power heads back toward the transmitter. I hope you're using your reflectometer sliderule. (Lit # 5952-0948). Slide in 1.5 on the SWR scale and read the return loss of -14 dB. At the peak of the standing wave, the peak RF voltage is now 20% higher than the forward wave. The 20% comes from the .2 reflection coefficient also shown on the sliderule. If the phase of the antenna reflection, or the length of the line is such that the peak of the standing wave pattern sits right at the position of the connector pair, then of course, it is subject to 120% of the peak voltage of the forward wave. Likewise, a more serious reflection like a short or open would run up the voltage as high as 200% for a full reflection.

The opposite side of that reflection problem is that at the voltage minimums, the current in the line is greatest. Thus, if the SWR null (current maximum) happens to occur at the point in the connector where the pins mate, the contact resistance of the connector pins would get currents as high as twice the normal forward current of a well-matched line. Remember that dissipated power is related to the square of the current. The same sort of reasoning has to be done on rating estimates of things like a slotted line which has dielectric beads positioning the center conductor in the center of the outer conductor surface. If the voltage maximums happen to occur at the bead positions, the excess voltage may cause excess heat dissipation in the poly beads, to the extent they might melt, even though the line and pin contacts can handle the load. Dielectric losses often go up as the square of the applied voltage.

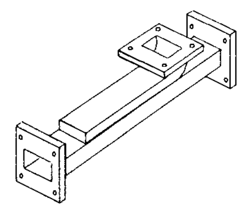
WAVEGUIDE AND COAXIAL POWER RATINGS

Generally speaking, our equipment is imbedded and built for instrumentation-type power levels of a few hundred milliwatts or perhaps in the case of some power sensors, 25 watts. On the other hand, we understand that customers often want to put one of our directional couplers into a transmission line carrying transmitter power and sample off 20 dB or 1/100th of the power to measure.

Let's talk a bit about power handling in waveguide. For the rest of this note, well be using the back-page reference data section of the Microwave Test Accessories Catalog, (Lit. #5091-4269E), August, 1992 which I will, henceforth, refer to as the MTA Catalog. If you look in the waveguide standard data chart you'll see theoretical CW power rating column. That was calculated by computing the maximum E-vector in the fundamental transmission mode of the guide (TE 10) and using a 15,000 volt per centimeter dry air breakdown at sea level, in addition to allowing a 2 to 1 safety factor. Note that the power rating varies from one end of the frequency band to the other even in the same guide.

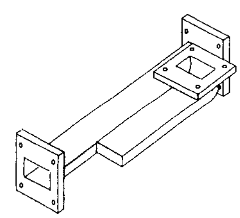
Take X-band for example. At 8.2 GHz, standard guide will rate out at 206 kW peak. That implies a clean guide with no little protrusions or solder bumps inside that could concentrate the E-field. Every new FE gets to ask the question, how much power can our HP 281-Series Coax-Waveguide Adapters handle? Well, obviously, they won't go 206 kW because not only do they have a full short on the backwall, but about one-quarter wavelength out from the backwall, protrudes a small 1-cm antenna from the Type-N connector on the flat side. Around the antenna is a polystyrene cylinder which helps shape the field from the cross-guide field into a field that has the little antenna stub as the center conductor of a coax line (the Type-N) connector.

So how much power? Well, we earlier decided that the Type N connector handles 5 kW peak if everything is clean. But we're pretty sure that the corners and sharp edges of the little poly cylinders might cause some field bunching. So we might recommend a safety factor of 2 for 2.5 kW, peak. And to allow for the fact that the transmission line or the load may not be well-matched, I'd allow another 2 to 1 derating for that for a suggested rating of 1 kW peak.



Broad wall low-power

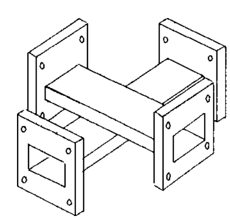
Now, for another matter on CW rating. We know that such adapters have about a 0.1 to 0.2 dB loss around X-band. If you look at your handy sliderule, you can see on the voltage/power ratio scales on the bottom, that a 0.2 dB reads out at about 1.045 power ratio. (I didn't actually read it to 3 decimal places, but in microwave work, you learn that for power ratios below 1 dB, you can approximately double the 0.2 and multiply that by 10 and get the 4.5% power loss.



Narrow wall higher power

Now let's try to put a CW signal with 1 kW through the adapter with a 4.5% power loss. That works out to 45 watts, and you can imagine it heating up too hot to touch. Let's estimate that the small plastic part can dissipate about 5 watts, unless it's well heat-sinked (consider a small 7.5 watt light bulb), which isn't bad considering that it might have a good heat sink on the run of other waveguide in the system. That would then translate upward to about 100 watts of RF rated CW

Naturally, the rating depends entirely on the loss in the adapter and certainly at S-band, there is less loss in the 2.6 to 3.95 GHz band. There may only be 0.05 dB loss in that band. Do you see how it's done?



Cross-guide "Riblet"

How about power ratings of something like a multi-hole directional coupler like the HP 752-Series? There are two problems with that one. First, these "broadwall" couplers have rows of perhaps 30 holes drilled in the top wall to couple off power to the secondary line for a precise 3, 10, or 20 dB factor. Those holes won't allow much high power to flow down the main line without breakdown.

The only coupler to recommend for high power in waveguide are called narrow-wall couplers. They use holes drilled in the narrow wall where there is no E-vector, but they lose some precision. Typically they have 40 dB coupling (1/10,000 power into the secondary line) because they are intended for lines carrying 100 kW and would thus have 10 watts in the secondary. Several companies including Narda/Loral and Systron carry these narrow-wall couplers. The advantage of the multi-hole coupler remains the fact that coupling is flat to ± 0.5 dB over the whole band. I would not recommend any main line power beyond a few hundred watts for our HP 752-Series multi-hole couplers.

Another system coupler that exhibits very small size is the so-called cross-guide coupler or the "Riblet" coupler which uses only two small X-shaped holes between guides. The couplers are only several inches long compared to the multi-hole types which can be 16 inches in X-band. Coupling factor typically varies by ± 1 dB across the band.

The second problem with couplers is that the secondary line uses a 1-watt termination on one end to absorb the unwanted-direction signal, and improve the directivity spec. Power headed down the line in a forward direction in a 10 dB coupler for example couples through to the secondary 10 dB down and keeps heading in the same direction. Our couplers have 40 dB directivity, so the imperfect signal coupled through and heads in the opposite direction towards the secondary load is 40 dB below that, or 50 dB below the forward signal in the main line (100,000: 1). That means that with a 1/2 watt load, you'd think you'd be able to run 50 kW down the main line. Not true, because if there is the slightest mismatch on the regular output port of the secondary line, let's say a 2:1 SWR, you get a reflection back into the secondary port only 10 dB down for a total of 20 dB from the mainline. That translates to 100:1 or a mainline rating of 100 watts.

Power rating of HP 382-Series Rotary Vane Attenuators is strictly limited, because the power gets absorbed by a thin-resistive-film sheet that lies along the horizontal centerline of the waveguide. In this position, the E-field of the fundamental propagating mode sets perpendicular to the resistive film in the end taper section, and therefore does not attenuate. When the center section rotates, its resistive film sheet turns all the way up to vertical which makes it now parallel with the vertical E-field. The signal thereby attenuates to a maximum of maybe 60 or 70 dB by the time it exits the center rotating section. For the angles in-between 0 and 90, the attenuation follows a cosine-squared relationship. The limitation to power rating, however is the maximum CW power the resistive film will dissipate, approx. 1 watt. For pulsed signals, the peak E-field will tend to break down the thin film, so we do not recommend any peak power beyond the specified CW value, typically 1 to 15 watts, depending on band.

Waveguide filters like the HP 362-Series look like a "waffle-iron" inside on the top and bottom walls of the guide. Thus, they decrease the vertical spacing to perhaps 10% of a normal guide height. That alone would reduce the power handling by at least a factor of 10 but in addition, the waffles have perfectly sharp corners and thereby bunch the E-field greatly. Further, the periodic reflected waves occurring along the waffles themselves could add or subtract and double the E-field again, at critical frequencies. So, power handling for filters should be de-rated by a factor of at least 100:1, maybe 500:1.

Frequency meters work on a "reaction" basis by sucking out a tiny bit of power through a tiny slot in the waveguide broad wall about 1/4 way in from the side wall. This tiny power resonates at the tuned frequency of the cavity alongside, and in turn, reduces the power headed along the main line by at least 1.5 dB. The tiny slot probably needs a de-rating of power of 50:1.

Waveguide cross-band adapters such as the HP MX292B that pass frequencies common to both bands previously used a true taper section from one band size to the other. Now we use stepped transitions paced one-quarter wavelength at the center frequency of the transition band. These also have the sharp corners that bunch the E-field and create limits on power. I'd say use a derating factor of 50 to one.

Coaxial coupler ratings are also problematic. Many are built with stripline techniques so they are captured between excellent dielectrics between ground planes. But often, right at the transition between the input Type-N connector, which has circular TEM field configurations as in coax cable, and the flat field configuration of strip line, there are sharp corners and sometimes even tuning screws that protrude close to the center conductor and make breakdown more likely. We recommend following only the specified power rating on coax coupler too, both CW and pulsed.

Low-pass and bandpass filter construction also limits ratings below that of standard guide or coax. For example, coax filters are usually constructed by stringing carefully-sized cylindrical slugs along the center conductor which extend out close to the outer conductor and form a shunt capacitor at that location. In between the capacitors, the center conductor is made thinner than a 50 ratio of diameters so that it forms an inductance at that location. By proper design, you get low-pass filter or bandpass filter action. But you also get very tiny spacing between the center and outer conductors and thereby reduced power handling. Instead of the typical Type-N rating of 500 volts, filters might only have 50 volts or power of 50 watts. Remember most filters don't have to absorb the unwanted power since most are reflective filters and the power heads back the line.

Coaxial switches like the HP 8761-Series or the HP 33311-Series use "edgeline" construction that sets a thin beryllium-copper center-conductor, maybe 0.1 inch wide on edge between two slab outer conductors. The edge of the HP 33311-Series center conductor stands only 0.007 inches from the outer conductor slab and thereby won't stand much voltage in the peak mode. Use the published ratings.

PIN diode switches, of course, depend on diode attenuation to perform their variable attenuation or full on-off switching. Therefore, they are subject to stringent diode-type voltage ratings, and being microwave diodes, dimensions are small and ratings low. Use the published ratings.

Fixed and moving terminations usually are constructed with a long, thin, iron-dust-loaded plastic pyramid mounted axially at the end of the guide. Since the sharp-pointed pyramid comes right down the very center of the guide, the main signal E-field hits it head on. The iron material doesn't break down electrically quite the same as the resistive material of the HP 382-Series, but it still won't absorb much heat/power beyond its CW rating.

The loads we've seen burned out usually lose the first 1 cm of a 10 cm pyramid. Use the published ratings.

Coaxial moving loads use a long, long taper which is inside out from a pyramid shape. Therefore, the first power absorbed in the load lies alongside the outer conductor metal and thus is well-heat-sinked. Use the published rating.

SWR OF THINGS

SWR of the cables is probably caused mostly by the connector itself. Cable manufacture has gotten pretty good these days, and irregularities in the extrusion of the plastic dielectric and the braiding of single, double, or triple braid coverings is normally not a problem. You can look up nominal SWR characteristics of some of the more popular connectors in the chart on the connector accessories page of the main HP Test & Measurement Catalog. For example, the Type-N connector shows a nominal SWR of 1.08 up to 18 GHz for a mated pair. These are pretty good figures for new connectors, but wear and damage can occur easily.

The SWR chart on the MTA CATALOG connector adapter page also puts you in the right ballpark for predicting performance for cross-series adapters, for example, Type-N to BNC. Use the worst SWR of the two and in the case of T-adapters, be sure to consider that the third port causes a shunt capacity which will give serious problems if the shunt arm is anywhere close to a quarter-wavelength in length. Even if the third arm is terminated in 50, you're still causing a standing wave in the line, because at the T-junction, the signal which had been traveling in a 50 line now looks at two 50 lines in parallel or a 25 characteristic.

There is a short history on the various popular coax connectors in the MTA Catalog. Only connectors with measurement implication are covered and you'll have to have your customer contact the manufacturer for characteristics on the others. For example, the TNC which uses threads instead of the BNC bayonet is used for high voltage applications and places where better shielding and a more rugged connection needs to be made. The BNC is great for video measurement connections, but system connections need more certain connection.

Incidentally, HP uses a special version of the Type-N connector for our 75 equipment. You'll be able to recognize it immediately, because the center pin is about 2/3 the diameter of a 50 Type-N which is about 0.065 inches. The center-conductor itself in a Type-N connector is 0.120 for a 50 version. If you know that the diameter ratio of coax determines the impedance of the line, then you'll recognize that a thinner center conductor makes a higher impedance. We use that special connector on the HP 8483A Power Sensor that matches 75 s. For the 50 MHz power meter calibration, you can adapt that 75 s to 50 Type-N with the HP 1250-0597 adapter to keep from breaking connector pins.

There are also some 75 versions of smaller cables and BNC connectors. They also use a smaller center conductor and care should be taken whenever they are used around 50 connectors, because the outer conductors and connecting nut fit together and could damage the center pin if mated. 75 s is popular for RF and video work.

For the last 15 to 20 years, HP has pioneered some more precise MW connectors for the purpose of improving our equipment specifications. In the mid-60's, we worked with an industry IEEE Committee to define what came to be known as the GPC-14 (General Precision Connector) which was a 14 mm outer wall diameter coax connector that was manufactured by the GenRad Company, who has subsequently retired from that business. The 14 mm connector was a super connector for low frequencies below about 8 GHz. Another company has since licensed the GenRad connector line.

HP had more interest and involvement with the resulting APC-7 (Amphenol Precision Connector) designed in conjunction with the Amphenol Corp, now a division of Allied Corp., and used by us in most of our 7-mm equipment. 7-mm specifies the outer wall diameter. The design used something called a "terminator" arrangement that permitted many of our products like couplers to have a standard fitting bolted to the product at the connector output point providing a standard coax interface. To that terminator interface, we can screw on a Type-N male fitting, a Type-N female fitting, an APC-7 sexless, high-precision connector, or a 7-mm sexed connector which permits bolted-together assemblies as shown on the HP 8761A Coax Switch data sheet where many switches are "treed" together. We call it the UT-250 connector.

There is one peculiarity with the two APC connectors. One of them, the APC-7 is trademarked by Amphenol, but the other APC-3.5 is not. That's why, in the T&M Catalog, the footnote only shows one trademark. Unusual, but perhaps just an oversight of a lawyer.

The next coaxial connector innovation was about 7 or 8 years ago with the APC-3.5 design. Again in collaboration with Amphenol, we have a connector that can work mode-free to 34 GHz and mounts on most of our precision 26.5 GHz equipment. There is a good reference to the design and the reliability and repeatability of the APC-3.5 in the article, "A High-Performance 3.5-Mm Connector To 34 GHz."

The article is particularly good in the data on connection repeatability, in comparison with the SMA, the industry standard for 3.5 connectors. Most of us know that an SMA connector is primarily designed for use inside systems where it may never get connected or re-connected more than 25 to 50 times in its life. That is nowhere good enough for measurement-type equipment that needs thousands of connections. One chart in the article shows a reflection coefficient plot done with automated data-taking where an APC-3.5 connector pair was connected/reconnected 983 times, each time rotating the pair by 90 degrees before reassembly. At the end of that brutal cycle, the SWR of the PC-3.5 pair still didn't exceed 1.01 SWR. Connector developments in the mid-80s focused on providing higher frequency operation to go along with system directions and the increased coverage of the HP 8510-Series Vector Network Analyzer. The 2.4-mm connector resulted, which provides outstanding performance to 50 GHz. The design strategy was to provide three different grades, production, industrial, and metrology. They are all compatible, and differ in price and performance.

Other manufacturers have designed connectors, too. The Wiltron Company offers the 1.92-mm size with coverage to 40 GHz, and 1.85-mm version have been designed by HP and others. It goes to 65 GHz. Naturally the trend is to buy and use three upper-miniature connectors in system designs for miniaturization reasons. But the downside is the terrific fragility of the center conductors, and the high transmission losses compared to similar lengths of silver or gold-plated waveguide.

WAVEGUIDE AND FLANGE TECHNOLOGY

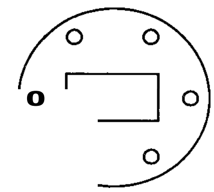
Waveguide tubing comes in the various sizes shown in the MTA Catalog. The band designation alphabet comes out of antiquity and WWII when radar was born in the Radiation Lab at MIT. The story goes that the original mechanical engineer who was building the first radar decided to use some available rectangular tubing. Thus, he went to the local hardware store in Cambridge, MA and bought some tubing intended for stairway banisters. It happened to have an outside dimension of 1 x 0.5 inches and an internal dimension of 0.9 x 0.4 inches. And so started the X-band we all know and dearly love.

The International Electrotechnic Commission (IEC) defines guide with numbers such as R-100. In the USA, the Electronic Industries Association (EIA) which was the surviving organization of something called RETMA (Radio and Electronic Manufacturer's Association) uses very logical designations of WR-( ). A WR-90 guide for X-band means waveguide/rectangular with an internal large-dimension of 90 hundredths of an inch. The British use another scheme and our own military use a JAN (Joint Army Navy) designation for transmission lines that cover both coax and waveguide. Notice that there are different designations for brass and for aluminum and, for some of the higher millimeter frequencies, silver.

This may be a good point to insert a comment about the band designators that exist. Perhaps in WWII, there were security reasons to code-name the various operating bands of frequencies. In any event, the bands did get designated from L-band to above 100 GHz. The common industry acceptance has not carried over to all companies, and in fact, HP is out of step on a few. Look in the MTA Catalog to find common industry usage, HP definitions, and those of other manufacturers as well. In addition, there is still a different band shorthand for coax and for electronic warfare bands. There is no right or wrong here. What you do is follow the lead of your customer. If their airborne radar operates in the 15.5 GHz area, he/she may call it Ku-band, while HP will call it P-band, and other manufacturers will call it U-band.

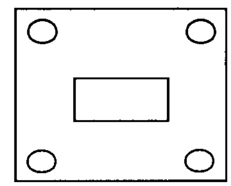
Since the traditional system construction techniques used rectangular tubing and hard-soldered the flanges to it, flanges were specified separately. But as HP began to design more precise measuring-type equipment, we often wanted to use a single aluminum casting or machined part that included both the open guide as well as the flange together. Many of our waveguide products are like the HP X281A which combines the functional body with the flange in a single die casting. That is why we usually write our specification as "Equivalent waveguide" or "Fits waveguide flange."

There is a brand new military spec system just introduced. We've put it into the new tables of the MTA Catalog. Waveguide tubing is defined in specification MIL-W-85 and uses the so-called slash number scheme typical of military numbers. Thus, the waveguide size for Q-band covers the 33.0 to 50.0 GHz range and is designated MIL-W-85/3.010 and is equivalent to WR-22. Is that clear? Likewise, the flanges for the same band are MIL-F-3922/67B-006. Sounds like a more-complicated way to say UG-383/U which was the old way to say flange. But that's the way our customer's world is and we adapt.



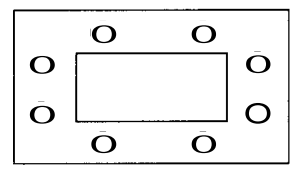
Circular Military

The military doesn't use each and every available waveguide size. For example, since the communications manufacturers have an allocated band at 3.7 to 4.2 GHz, the waveguide size WR-229 fits their job better because the terrestrial comm systems operate closer to the center of frequency of that waveguide tubing, and therefore are easier to get phase delays and performance better optimized. But since the military doesn't use that band, they don't specify the guide. The EIA flange are also nicely logical. A cover flange is the CMR-229. A pressurized flange with an 0-ring which can be installed outside in tough weather is a CPR-229. Neat and clean!



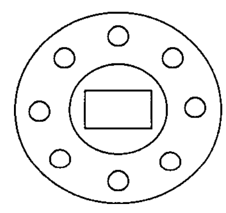
Square Military

Next, let me explain the difference between a cover flange and a choke flange. Virtually everything we sell uses cover flanges so you can look at the catalog or an HP waveguide product and notice that the cover flange is perfectly flat and mates with another flat-surfaced flange. HP takes extra special care to use a lapping process much like lens lapping that creates a flat surface with 30 micro-inch smoothness and a convexity of 30 micro-inches per inch. You can see that bolting two of those surfaces together will cause the very inner edges at the facing waveguide hole to touch first and when the circumferential bolts are pulled down tight, the RF currents flow right across the facing contact points for low loss and low mismatch.

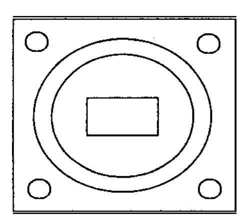


Rectangular CMR

Cover flanges are rectangular for the CMR types and use eight holes in an alternate threaded hole, "clearance" hole sequence (clearance means the hole is unthreaded). Thus, the bolts come in alternately from each side, and need no nuts since each alternate flange hole is threaded. Cover flanges for most of the military bands up to 8.2 GHz are round with open bolt holes, no threading. Bands up to 18 GHz are square with 4 clearance holes. But as the frequencies get up into the "millimeter" range (30 GHz), the alignment precision become much more important, so there are available circular flanges with 2 alignment pins which fit into opposing alignment holes in the opposite flange. Then, there are 4 tapped holes which use some special bolts that enter alternate from opposite sides. The special screws are thus captivated in each flange and need no nuts. These flanges are most important for frequencies up to and beyond 100 GHz. See the diagrams in the MTA CATALOG.

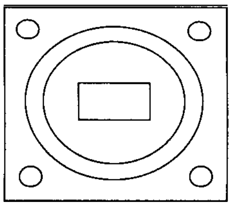


Circular Precision

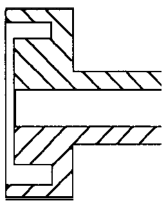


Choke

Finally, while we don't sell choke flanges, here is what they do. As mentioned, many systems work outside in the rain and ice. The system engineers usually try to pressurize the guide with dry nitrogen to keep moisture from getting inside and freezing. Microwaves are literally dead in moisture, so that is important. The choke flanges usually have an 0-ring groove which, when opposed with the above mentioned cover flat flange make a nice tight pressure joint. Further, a choke face also machines a circular slot into the thicker flange which in X-band is about 0.020 inches wide and about 1.3-inches in diameter, just cutting outside the waveguide



Face View



Side View

hole corners. The slot is machined about one-quarter wavelength deep at mid-band, about 0.3 inches deep for an X-band flange.

Here's how it works. The bottom of the slot is obviously a short. One-quarter wavelength away, microwaves think they see an open circuit. Now, that point is on the surface of the flange and about a quarter wavelength still from the edge of the waveguide opening itself, which now looks again like a short, and happily transmits the microwave energy along the waveguide hole just as if those surfaces fitted perfectly. Actually the main reason for choke fittings is to permit the less-precision assembly in the field without causing system degradation. Virtually all measurement applications use cover flanges so you won't normally have to worry about it.

HOW DOES VARIOUS EQUIPMENT WORK OUTSIDE ITS NORMALLY-SPECIFIED BAND?

There's no good single answer for this. But that doesn't prevent customers from asking you often. You need to know something about the inside design of the product and a few principles, so here goes. Let's do an easy one first.

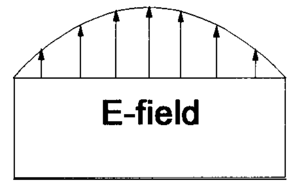
Directional couplers sometimes need to be used outside their range. The waveguide multi-hole type (HP 752-Series) have coupling factors that vary in a smooth curve about ±1/2 dB across the band. You can generally extend these curves for 10% or so outside the normal bands. I think many of you realize that the fundamental mode (TE 10) in waveguide is all by itself for about 1.5 to 1 frequency range or a 50% band. For example 8.2 to 12.4 GHz is 50% (12.4/8.2 = 1.5). Beyond that other modes have a chance to join in and spoil the performance.

For the TE 10 mode, the lower cutoff frequency for X-band guide computes out at 6.56 GHz. That means that the TE 20 or TE 01 mode can begin to propagate in the guide at 2 times 6.56 or 13.12 GHz. Those are the frequencies where you can start to get unwanted effects from the other modes. The problem is that with unsymmetrical protrusions inside normal waveguide, the signal flow can be flipped from one mode to another. Then, since you designed your coupler to use those 30 carefully drilled holes to depend on the TE 10 mode configuration, but now they are no longer quarter wavelength, but instead half-wavelength, or if it flips to a TE 01 mode, the holes on the broadwall of the guide don't have any effect at all.

There is a good example of intended extension of waveguide beyond its expected band limits. The usual frequency range of J-band is 5.85 to 8.2 GHz. But the Navy had a shipboard fire-control radar that was allocated in the band 5.4 to 5.9 GHz. While they could have used the next bigger size of guide, they chose to extend downward to 5.4 and asked HP to check out all our J-band test equipment for their application, which would mean a lot of potential sales. We did, and found that this 10% extension below the usual limit worked for just about all the specs. It, of course, did require writing new test procedures and special ordering routines.

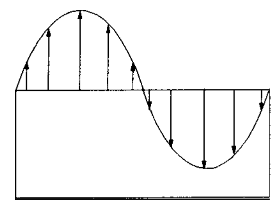
Here's a reminder of how the E-fields of several simple modes look.

Notice that the design of our HP 281-Series of waveguide coax adapters has a small antenna probe sticking down through the center of the broadwall of the guide as shown above, to couple with the vertical E-field of TE 10 at the center of the guide. With this coupling design neither of the modes TE 20 or TE 01 field would couple properly.

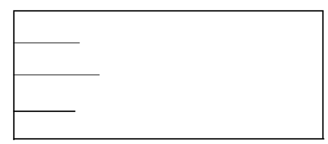


TE 10

The point is that since the specified band is 8.2 to 12.4 GHz in our example, and the net unwanted modes can start to propagate at 13.12 GHz, my 10% band-extension estimate could start to get us into trouble. Actually, you have to be some distance above the cutoff frequency to get good transmission. You can see this from the ratio between 6.56 (cutoff) and 8.2 GHz lowest recommended frequency), for TE 10.

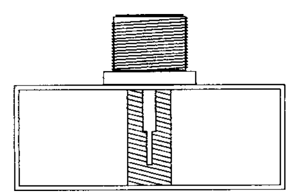

TE 20

Incidentally, we use this cutoff phenomena quite a lot in microwave design. The signal attenuation in a "waveguide-beyond-cutoff obeys a fundamental mathematical law. Our old klystron signal generators used a tiny circular hole (which formed a waveguide-beyond-cutoff) milled into the oscillating cavity to bleed off a precise amount of signal power. You calculate the amount of signal reduction vs. distance with a ratio of the diameter of the hole vs. the electrical wavelength.


TE 01

A typical characteristic for an X-band generator was a hole about 0.125 inch diameter and a probe pickup loop that experienced about a 34 dB per diameter movement. It was extremely precise and unaffected by almost any environmental effect, only the precision of the hole cut into solid brass and the precision of the gears driving the moveable probe.

Regular rectangular guide as shown above, also provides a certain mathematical signal reduction vs. distance in the guide. For a frequency well beyond cutoff, (2x to 3x below cutoff frequency, f_c), the signal reduction works out to 34 dB per width dimension of the guide. This would mean if a signal exists at one point in a guide with 1-inch internal width, and it is well-below cutoff, that its strength down the guide will reduce by 34 dB per inch.


HP 281A

Incidentally, this is the principle of one form of EMI shielding that is so important now. When you bottle up RF or microwave signals, you try to use internal dimensions that will not propagate signals in a waveguide mode for that particular frequency. For example, if you have a phase-lock loop operating at 1000 MHz, the quarter-wavelength of that frequency is 7.5 cm, so you'd try to keep the internal dimensions of shielding boxes less than that number or you might set up a cavity you didn't want. Incidentally, that analysis fails if any conductor runs down the center of the cavity and makes it into a pseudo-coaxial transmission line.

Back to couplers. Coupling was pretty-well behaved. SWR is not, usually because the returning wave that makes up an SWR signal comes from a number of separate reflections inside the unit. So, that is why most SWR curves show lots of up and down variations throughout the specified band. But in turn, it makes SWR more unpredictable outside the band.

Directivity of couplers is pretty unpredictable, too, since it depends on its low value on getting a whole lot of signals coming from the many multi-drilled coupling holes to add up to zero. Or at least 40 dB down. It's usually difficult to get 40 dB within the specified band, and outside things get difficult indeed. But if customers can live with lowered values of directivity, you can often get 20 dB without too much trouble at 10% extensions of the band limit.

If you know the construction principle of a product it might help. For example, the HP 281-Series Adapter mentioned above has the little antenna probe mounted one quarter from the backwall short. The quarter-wavelength is assumed for the center operating frequency for the particular band, let's say 10.3 GHz for X-band guide. But then, at twice that center frequency, the backwall short translates to a short right at the probe itself. And the SWR would probably go infinite in both directions, down the guide or out the coax.

INSERTION LOSS OR "RESIDUAL" ATTENUATION

Out-of-band insertion loss of a component is usually well-behaved too. This term is often called residual attenuation. It's what you get when you open a line and put in a component like a rotary-vane attenuator. Insertion loss usually varies as the square of the frequency since it is mostly skin losses in the current flow. But if the component has dielectric parts like the resistive films of the HP 382-Series, then those losses figure in too.

ROTARY-VANE ATTENUATORS

The attenuation of rotary-vane attenuators like the HP 382-Series depends on getting at least 70 dB loss when the circular-guide center section has the resistive film standing straight vertical. If that is true, then the cosine-squared theta mathematical relation holds up well up to the indicated direct-reading value of 50 dB. The problem is that to get at least 70 dB of loss max, you need a certain number of wavelengths along the resistive film. Since the wavelengh gets longer below the specified lowest frequency, you no longer get 70 dB maximum, and therefore unpredictable values. It is not recommended to go more than maybe 5 percent below the lowest specified frequency.

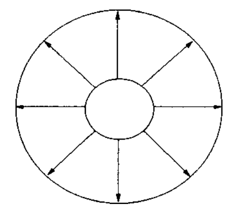
On the high frequency end, the problem comes with the fact that circular guide starts with another mode long before the rectangular guide in the end taper sections does. That mode totally fouls up the cosine-squared relation. Don't depend on the rotary-vane much beyond about 5% of the upper-specified frequency.

All this is not to say that rotary-vanes won't give smooth, variable attenuation at 10% outside the band. In fact, they probably do just fine when used for level setting when you have other means of reading the power level you want, and not depend on the direct-dial reading.

COAX COMPONENT LIMITS

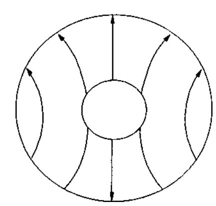
Coax component's performance are easier to predict in some ways and more difficult in others. Since they are designed for many-octave use, you don't use the 1.5 band factors characteristic of waveguide. Basically, coax must be designed for full matched-line performance throughout its entire frequency range. The usual top frequency failure of coax comes when the normal TEM transmission mode with the E-field from center conductor outwards axially to the outer conductor is no longer the only mode that can be supported inside the coax line. That happens when the frequencies get high enough that it can support a waveguide mode. See the diagram.

For example, the APC-3.5 coax (3.5-mm outer diameter) has its first waveguide mode at around 37 GHz and therefore it is rated to 34 GHz. The SMA connector is rated to about 22 GHz, but people actually use them beyond 26 GHz by being careful to not design in non-symmetries.



TEM

The next problem with coax when used beyond its rated range is the cavity-type modes that can set up inside the support beads of the connector itself. In Type-N, the bead resonance comes in at about 19.2 GHz, so you can see why we are careful about specifying performance above 18.6 GHz. In a pinch, you can easily use Type-N coax well above 18.6 GHz, but expect tiny resonances or "suckout" to take place with very sharp skirts that can, run 3 to 5 dB. That's disastrous for a measurement situation, but may be quite tolerable if you're just trying to run a signal to an analyzer to look for ratios, and not absolute power.



Guide Mode in Coax

DETECTORS

Most of our instrumentation uses of microwave detectors are recommended for the so-called square-law range. That means power input is proportional to video voltage out. The HP 415E SWR Meter shows calibration in those terms. And if you put a microwave pulse on a scope, the vertical scope scale (linear) comes out nicely calibrated in linear power terms. That allows for easy measurement of pulse width at the half-power points or for determining the rise/fall times at the 10 to 90% power points.

You'll need to load the detector output with a resistor selected for best adherence to square-law over the range up to about 0 dBm. We sell them with the right specified option. All those interactive parameters of the diode design and application can be learned by referring to several documents. The HP 33330B/C data sheet shows a number of curves that relate input power vs output voltage, called the transfer characteristic. Naturally, the output varies with the value of the shunting load resistance since it works against the equivalent video impedance and loads down the sensitivity.

Another curve shows the variation from square law as you go higher than the nominal natural range around -20 dBm. Most of these parameters vary somewhat with temperature such as the video output impedance, the tangential sensitivity and frequency response. Such information becomes important if you are a designer planning on using the detector inside a system where it will level power or serve as a CW or pulse monitor.

The other document useful to understand diodes from the basic physics of the chips through Schottky vs point-contact, to the embedding theory of getting the chip matched into the coax transmission line, to the external performance characteristics is the technical paper reprint, Characteristics And Applications Of Diode Detectors, by Ron Pratt. You can request a copy from your friendly MID RSE. Be aware that the publication is in the form of lecture notes, so it is a bit cryptic, but highly useful.

Above about 0 dBm, detectors go into a quasi-linear mode and then finally go into the linear range. Of course, the linear range is what you want for mixer action. Our standard "video" detectors aren't preferred for mixers since the output has too much capacitance for getting useful signals at the IF frequency. The sensitivity would probably be bad and the noise figure of the down-converter would certainly suffer.

On the other hand, spectrum analyzer mixers are fine for up-and down-conversion work. The single-balanced and double-balanced technology also provides useful local oscillator rejection, etc. We recommend those for the down-conversion on the noise figure meter measurement set-ups above 1500 MHz for example. HP MSD makes some double-balanced versions and there are plenty available from industry. Mini-Circuit, RHG, Avantek, and W-J come to mind.

For the absolute-best square-law characteristic, use a power sensor that has a thermocouple element. They depend on heat to drive a thermocouple for output. And heat is pure square-law. Furthermore, our thermocouple power sensors operate above the extended top range of a square-law-loaded diode which stops at 0 dBm, and thermocouple power sensors work all the way to +20 dBm.

TERMINATIONS

Most of our terminations and moving loads and shorts work well outside their specified frequency limits. The main limitation is that the normal use of a sliding load or short is to move the reflection vector through a full 180 degrees so that vector analyzers may be calibrated for a full circle. This simply means that if you use frequencies too much below the lowest limit, you can't get a full half-wavelength of movement. That's an application question. There is one design snag with several of our HP 920C-Series Sliding Shorts which use a micrometer barrel to a choke-type short, rather than a contacting-type short along the waveguide. The chokes are slotted rings cut into the shaft and they work best only in the specified guide band. Outside that, they don't produce the 100:1 types of reflections that we like to see from our best shorts.

EDGELINE

One of the key design concepts of some of our coaxial products is the "edgeline" transmission line. It results in the excellent SWR performance of our microwave switches and step attenuators The concept is explained in Application. Note 332, and in more technical depth in these references:

"Broadband Passive Components For Microwave Network Analysis, Hp Journal For January, 1969, And Coaxial Components And Accessories For Broadband Operation To 26.5 GHz, HP Journal For June, 1977."

For step attenuators like the HP 33320 family, the bunching of the field lines at the edge of the center conductor permit flexure of the center conductor and the basic "flipper" action to switch in and out the thin-film-on-sapphire resistive elements. But, dimensions are tiny; 0.007 inch spacing for the HP 33320 type attenuator. So you can't extend operation to higher frequencies more than a few percent without running into new modes and unpredictable performance. They already do work DC to 26.5 GHz, so that's a lot to ask.

Incidentally, while the HP 8761/33311 family MIDT switches can handle some relatively high powers like 10 watts on a CW basis, they don't "hot switch" it very well without burning the contacts. If a customer has an application that can turn off the transmitter before switching the signal, then turn the power back on, it's a go. If the power must be hot-switched, then stay with the nominal rating of 1 watt.

ATTENUATOR PADS

The resistive pads of many of our coaxial products use a distributed film design concept that depends on the shape of the film to result in certain attenuation value. Thus, the loss does not depend on the specific value of the s-per-square resistivity which is hard to control and varies with time and temperature. These pads have excellent performance, and the newer ones like those used in the HP 8493C Pad are specified to 26.5 GHz but work mode-free right up to the limit of the APC-3.5 connector at 34 GHz.

IMPORTANT CHARACTERISTICS FOR VARIOUS COMPONENTS

I suggest that you read the introductory page to each product section in the Coaxial And Waveguide Catalog to learn about specific manufacturing features of the various products. For example, you'll learn how we conservatively specify our coax pads with guard bands on the specs. You'll learn that for slotted lines and sliding loads, that the internal guide dimensions have high regularity because we broach to internal surface which most others do not do.

READING REFERENCES

RADAR

Introduction to Radar Systems - Skolnik

A true introductory text by the "Father of Radar."
McGraw-Hill, 1962

ELECTRONIC WARFARE

The History of U.S. Electron Warfare - Price

A good backgrounding test for the EW beginner covering year 1939 - 1946 with focus on U.S. operations.

Association of Old Crows
2300 Ninth Street, Suite 300
Arlington, VA 22204, $22.50

Instruments of Darkness - A. Price

A comprehensive history of electronic warfare operations during WWII, by English author Alfred Price, focusing on British/German activities.

Charles Scribner, New York, Printed 1978

Applied ECM - Van Brunt, 2 volumes

Detailed descriptions of countermeasures hardware and operations.

EW Engineering Inc., Printed 1982
P.O. Box 28
Dunn Loring, VA 22027

SURVEILLANCE/INTELLIGENCE

Puzzle Palace

An overview of the organization and operation of the National Security Agency. Gives good insight into "black" work and communications surveillance.

The Falcon and the Snowman

A true-life paperback novel of the TRW employee who sold the instruction manual of the Big-Bird surveillance satellite to the Russians. Some insight into CIA work and satellite surveillance hardware. Made into a U.S. motion picture which is quite entertaining.

Deep Black

Extensive review of U.S. intelligence and surveillance operations from the 1930's. Particularly good in describing the political scene as well as a very up-to-date look at the technology.

COMMUNICATIONS

Digital Communications-Microwave Applications - Feher

The microwave slant on digital communications.

Prentice Hall, v1981, Pub. #13-214080
Englewood Cliffs, NJ 07632 $28.50

Digital Communications-Satellite/Earth Station Engineer - Feher

Theory and practice of design and test in digital communications for earth stations and birds.

Prentice Hall, v1981, Pub. #13-212068
Englewood Cliffs, NJ 07632

Transmission Systems for Communications - Bell Telephone Staff.

A basic text on design theory of FDM multiplex and radio used in ATT.

Western Electric Co., Technical Publications
Winston Salem, NC

GENERAL/MEASUREMENTS

Microwave Theory and Applications - Adam

A measurements-oriented text ranging from S-Parameters to detector characteristics, written by well-known author Steve Adam, who recently retired after 25 years at HP SPD.

Prentice-Hall, Pub. #13-581488
Englewood Cliffs, NJ 07632
(HP organizations may order from CPC Part #9320-2011 at $57.50)

Electromagnetic Spectrum Wall Chart

Printed 1972, $5.00 2 x 3 ft., 4-color chart

Electronics Week Books
Dept. E213, P.O. Box 541
Hightstown, NJ 08520 (609) 426-5070

MEMBERSHIPS

Electronic Warfare

$15.00 per year
(includes subscription to Journal of Electronic Defense)

Association of Old Crows
2300 Ninth St. Suite 300
Arlington, VA 22204

Military Communications

$15.00 per year (US)
(Includes subscription to Signal Magazine)

Armed Forces Communications and
Electronics Assoc. (AFCEA)
4400 Fair Lakes Ct.
Fairfax, VA 22033-3899

GENERAL REFERENCES

Reference Data Book For Radio Engineers

ITT Howard Sams & Co., Library of Congress # 43-14665
Indianapolis, IN

A High-Performance 3.5-mm Connector To 34 GHz.

Pub. July 1976 issue of the Microwave Journal