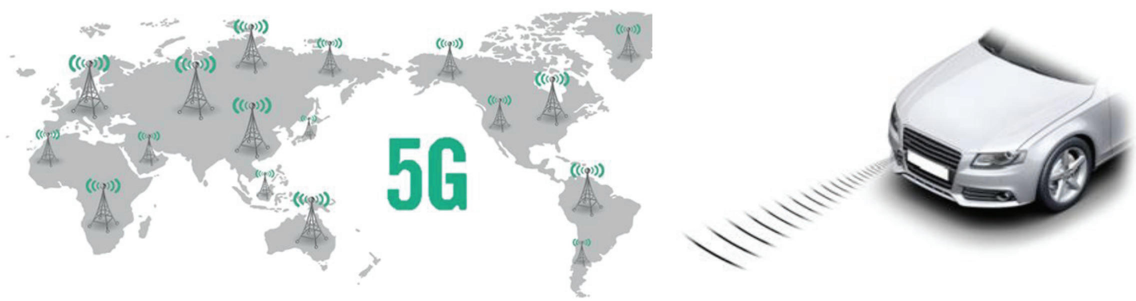
Application Note

Anritsu envision : ensure

Advantages of Coaxial Connectors for Data Transmission over 100 GHz



Electronics technology is evolving every day, which necessitates that communication data transfer increase bandwidth to accommodate more traffic. To get larger bandwidths, we must move up in frequency. Over the last few years, there has been a lot of research and development in millimeter-wave (mmWave) frequencies, especially in the W band (75 to 110 GHz). Some of this growth is fueled by new requirements for automotive radar and wireless communications. 5G communications promises gigabit data rates along with extremely low digital communication latency, which has translated into a need for new backhaul, front haul, and fixed services solutions at or over 100 GHz. Not only will this trend of moving up in frequency require W band support, many 6G roadmaps confirm a move into F and D band frequencies.

This begs the question, why move to the F or D band for telecommunications? This simple question can find its answer in a gradually expanding world of connected devices. Moore's Law gives some insight to this move because as technology grows and becomes cheaper, adaption and acceptance of connecting everything and everyone will grow and require more bandwidth resources. This requirement for higher bandwidth will drive the use of higher carrier frequencies. Even for lower carrier frequency systems, the requirement for harmonic testing may drive F and D band measurements.

Projections for device connectivity says billions of devices (IoT) will communicate by 2030 including handset communications, apps, internet streaming, machine learning, and eventually many AI systems interconnected amongst all of them. The market drivers of these frequency requirements are very clear, but what should be expected about the design and implementation of the devices? What will need to change to address devices that can move data in such high bandwidths through networks? The simple answer is an interface that can propagate a broadband signal with little impact on the fidelity of the signal.

This application note will explore historical challenges for making both frequency and time domain application measurements, advantages of using coaxial components, and what connectors are available that support engineers that want to move devices into the mmWave frequencies.

Waveguide Characteristics

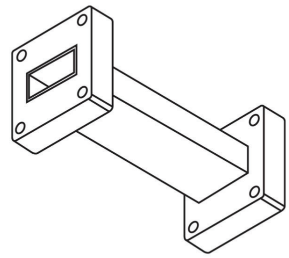


Figure 1. Generic Rectangular Waveguide

Waveguides are proven technology that have worked for nearly a century (Figure 1). One of the many attributes for waveguides is that they are nearly lossless. This is the case because the field amplitudes do not peak at the walls in the fundamental mode for waveguides. They can also address frequencies in which there are still no solutions for an interface up to the terahertz range. As technology advances into higher frequencies, waveguides will still be needed for many applications, but as applications mature and design/testing requirements are laid out, they may not offer the right electrical or mechanical properties for addressing specific application requirements.

Frequency Scalability

Waveguide theory suggests that there is a minimum frequency (cutoff frequency) or mode at which a waveguide can operate and a maximum frequency before the introduction of new modes. Because of this limited frequency coverage, waveguides are generally referred to as a banded interface because all frequencies below the cutoff frequency face such high attenuation (the frequency response will resemble a high pass filter). There are some ways of extending a waveguide’s coverage, but it will only result in a modest increase in frequency range and not quite result in broadband coverage.

In general, there is some overlap between waveguide bands (Figure 2). Some may wonder why worry about such issues for applications that fall within that range? This is a valid question, and for those key applications a coaxial connector may not be warranted. For many other applications, this is just simply not the case and broadband frequency coverage up to the desired frequency is more useful for measurements.

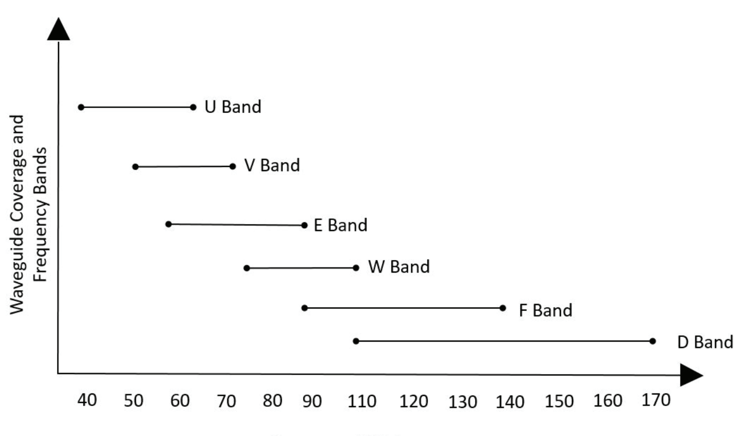


Figure 2. Waveguide Coverage and Frequency Graph

Dispersion

Dispersion is the phenomenon where group velocity of signals vary based on frequency. This is an important characteristic of waveguides that should be mentioned because this behavior can influence signals. For measurement purposes, dispersion can be checked through group delay analysis. From the below graph (Figure 3), it is clear the group delay has an effect on waveguide linearity vs the linearity of coaxial connectors.

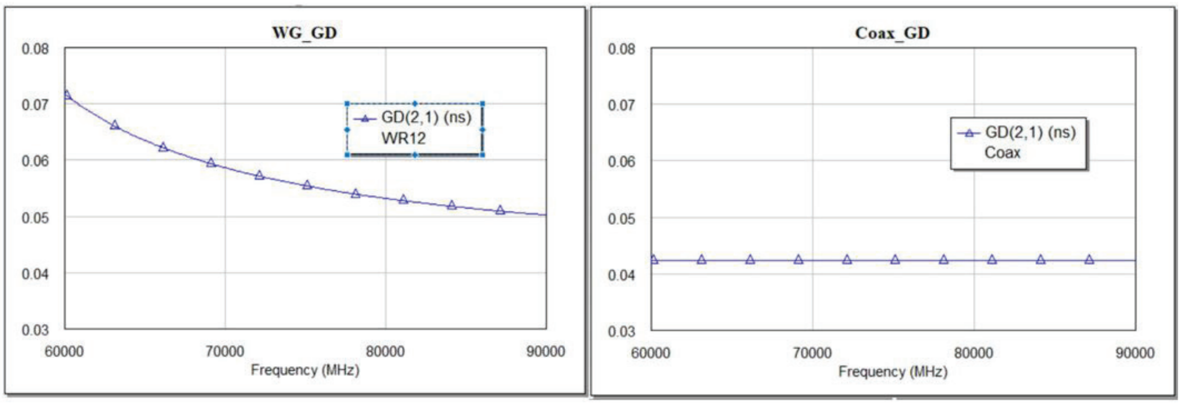


Figure 3. Group delay vs frequency for waveguide and coaxial respectively

From the equation of group delay, it is also evident, mathematically, how frequency dependent factors can be affected by dispersion.

$$Group\ Delay = -\left(\frac{d\varphi}{d\omega}\right)$$

where φ is phase velocity and ω is 2*Π*f.

Measurement Setup

One of the very subtle ideas about any setup is the complexity that is involved. Certainly for any engineer that wishes to make a measurement, the idea of completing the measurement with repeatable results and a simple setup should be priority. For waveguides, setup is generally an easy process for the much larger, lower frequency components with the exception of a setup using a cantilever. It is well known that in some test facilities, waveguide components are fastened using binder clips and while this way of connecting interfaces may work, it is certainly not a good approach for making measurements.

Like their coaxial counterparts, waveguide interfaces shrink in size as the application space moves further and further up the frequency pole. These smaller interfaces (Figure 4), especially at the E, W, F, and D band, require much more attention to detail. It is possible to misalign apertures because the dimensions are so small. Proper care should be exercised to align apertures, assure mating surfaces are debris-free, and fastening devices are implemented.

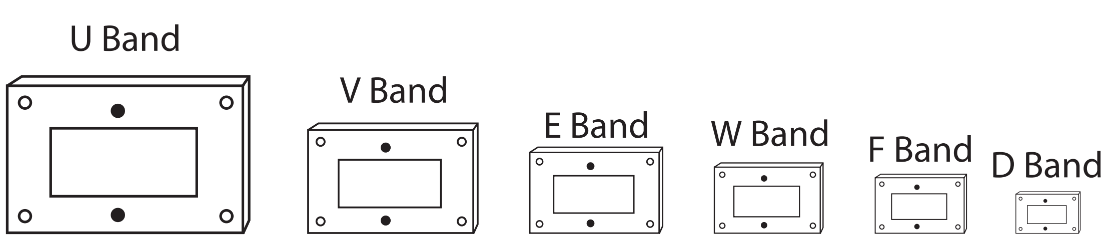


Figure 4. Waveguide Illustration to Demonstrate Size Dependency on Frequency

The interfaces between two waveguide surfaces has been considered, but what happens when a coaxial interface is introduced? Test ports on most test equipment are becoming increasingly coaxial and so any connection to a native waveguide interface requires an adapter. Besides the effort of characterizing the adapter and de-embedding that network for accurate measurement analysis, adding an adapter can be a costly endeavor at frequencies above 100 GHz. It was mentioned earlier that waveguides do not have much insertion loss, but this is no longer true when a coaxial adapter is introduced.

A very important quality of a measurement is how repeatable it is. Ideally, the results from one measurement done by one individual should have no issues with the same setup done from another individual. There should be correlation as all things being equal would suggest this is easy to accomplish. Waveguides are remarkably known for possessing the ability to change performance between users. To remove this issue from a measurement, many design steps have been taken to help users increase repeatability. One such design is the use of guiding pins that not only align apertures but ensure the interface is matched perfectly. There are also holes in waveguide components that allow interfaces to be fastened to each other using screws (Figure 5). While this is a good addition for users, it can be time consuming between measurements.

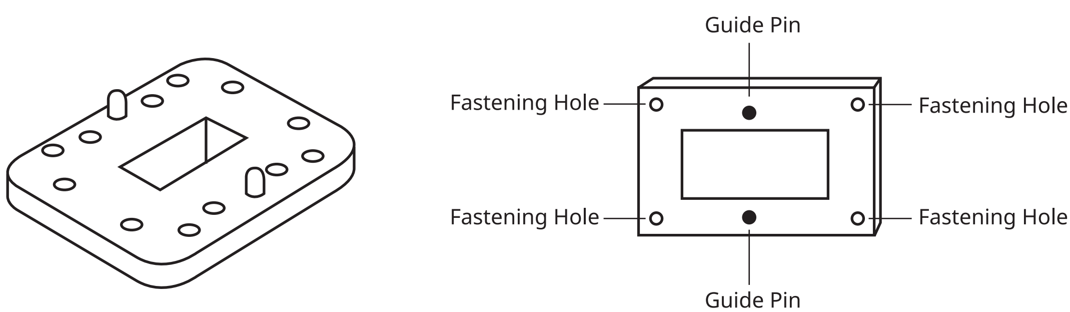


Figure 5. Waveguide Component with Matching Alignment Design Diagram

Waveguides are good components that have stood the test of time. Waveguides certainly have their place in the measurement world, but where do they fall short and what challenges come from these short falls?

Historical Challenges

Historically, waveguides are the first component that comes to mind for almost any type of measurement up to 100 GHz and further. The main reason for this is because they are easy to fabricate in a shop and nearly anyone can make a waveguide since the frequency bandwidth is based on the aperture dimensions through a few simple calculations. Another reason is because the testing environment around frequencies past 100 GHz have not had much support with coaxial components. Waveguides can most certainly be used for many measurements, but what challenges are presented by waveguides? For generality, we will consider the rectangular waveguide operating in a TE10 mode and there is an assumption that readers will have bit of knowledge about this technology.

Frequency Domain Challenges

The biggest trade-off that waveguides face is the inability to provide frequency scalability. There are new applications that are pioneering the need for mmWave frequency coverage that would be hard to address with waveguides. One such application would be SERDES harmonic NRZ testing. For bit rates larger than 32 Gbps with a pulse faster than 10 ns, a 3rd and 5th harmonic evaluation will land in the 48 and 80 GHz range respectively. While 32 Gbps is an arbitrary speed, it is a technology already in use in backplane designs for 100GBASE boards and is a common topic at any technology conference or trade show. While this is only one example, the reality is that this technology is only going to require more speed which means higher frequency. There are many companies floating the idea of 56 Gbps for applications, but what if the change in rate is minor from the already existing 32 Gbps and we consider a 40 Gbps rate. The 3rd harmonic is at 60 GHz but the 5th harmonic is at 100 GHz (Figure 6). It should be clear that for higher rates, the 3rd harmonic may easily be over 70 GHz. From this prospective, it would be impossible to use any interface other than coaxial.

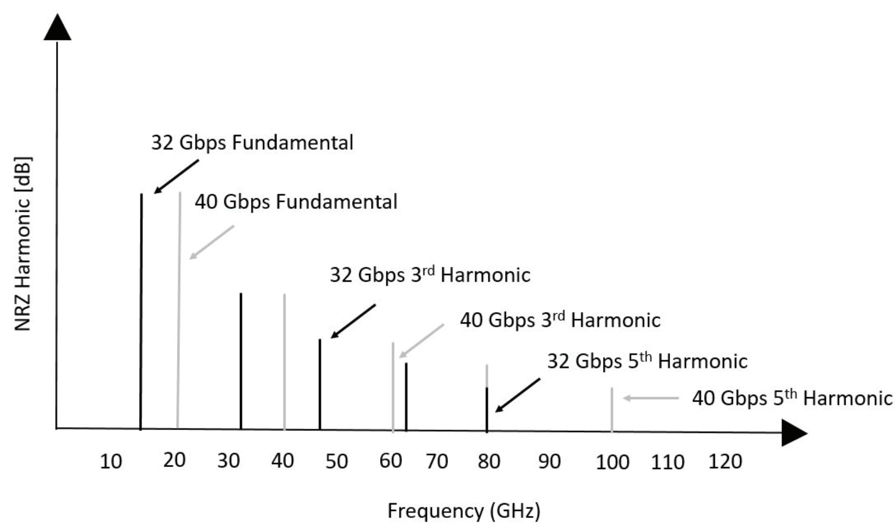


Figure 6. NRZ Harmonic Plot for 32/40 Gbps with Corresponding 3rd/5th Harmonics

While we are on the subject of high-speed data, many view optical communications as a high-speed digital connection. Like high-speed data, opto-electrical devices require not only a characterization of the opto-electrical device, it also requires a broadband characterization of the optical-to-electrical (O/E) or electrical-to-optical (E/O) standard.

If the subject of frequency coverage has not created enough challenges in the frequency domain, the idea of biasing also needs to be addressed. For nearly all device testing there is always a power aspect. One could argue that for many devices, power, in general, plays an important part of the measurement. Radio frequency (RF) power transmitted and received through a device is not the only power that a device sees. Many devices categorized as active require an external direct current or DC (0 Hz) signal input, known as a bias, and often this bias needs to be applied on the same conductors as the RF.

For any transceiver, most likely used in telecommunications or automotive radar, there will certainly be amplifiers. How does one test them when they are used past 100 GHz? In many cases, components like bias tees are used but there no such component exists in the waveguide world. Interestingly enough, the design of a bias tee in the coaxial world can be constructed from a DC block in parallel with a capacitor, and while a waveguide cannot pass a DC signal and acts a DC block, this exact same electrical property prevents it from become a bias tee.

Time Domain Challenges

Many applications not only require frequency domain measurements like insertion and return loss, but also time domain analysis as well. While a large bandwidth coverage provides much more resolution into the impedance characteristics and low pass time domain processing (providing even more resolution and step responses, which then allows eye diagram generation), it also requires a harmonic calibration. If the start frequency is the lowest frequency for a harmonic calibration, it would be impossible to do a good harmonic calibration using a component that has the lowest frequency at 75 GHz but only spans 110 GHz. This low pass type of measurement is unavailable with waveguide.

As mentioned earlier, dispersion is a characteristic of waveguides and can manifest itself as a distortion factor on the pulse (Figure 7). In fact, signals passing through waveguides will have to always consider this effect, and while most measurement equipment can handle an analysis of this distortion through the mechanism of dispersion, it should be mentioned that it can present issues, especially for other time domain techniques [1].

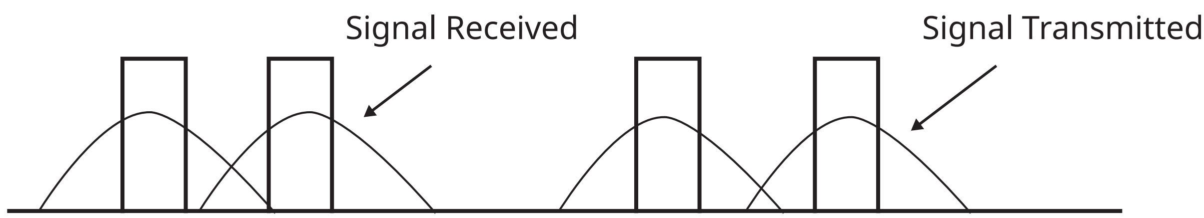


Figure 7. Distortion of a Transmitted Signal Due to Dispersion

Advantages of Coaxial Connectors for mmWave Interfacing

The first advantage that any user will have using coaxial connectors is broadband frequency coverage or frequency scalability. Coaxial connectors, like waveguides, do have frequency limits, however for coaxial connectors the frequency limit only exists on the upper frequency. While both interfaces can share a lot of the same terminology (yes, coaxial connectors use terms like TE and modes), the design and implementation of coaxial connectors is much different.

Coaxial connectors do not use apertures to define their frequency coverage. The frequency coverage of a coaxial connector is defined by the cutoff frequency of the next higher order mode which is dependent on the connector geometry, specifically the radii of the inner and outer conductor.

In general, and like waveguides, coaxial connectors will operate best in mono-mode conditions. The next higher order mode is based on a TE11, similar to waveguides, that occurs near the theoretical limit of the connector. The explanation for this behavior is that connectors use support beads as an all air dielectric is not feasible. From the interface of these support beads to the air dielectric, input signal energy can exchange between modes. Impedance and phase velocity mismatch become resonances or modes. Below is a table showing connector frequency coverage based on TE11 limits.

Coaxial line sizes of 50 Ω characteristic impedance			
Connector	Theoretical limit in GHz for onset of TE11 (H11) mode	Rated minimum upper operating frequency in GHz	Inside diameter of outer conductor in mm (nominal)
K	46.5	40.0	2.92
Q	56.5	50.0	2.40
V	73.3	65.0	1.85
W1	135.7	110.0	1.00
0.8 mm	166	TBD*	0.80

**0.8 mm connectors are currently used up to 145 GHz for many applications*

Frequency Domain Advantages

Having broadband frequency coverage for coaxial connectors not only allows this interface to be used for all types of active device, high-speed digital applications, and corresponding harmonic testing, but they are still able to address mmWave frequency requirements as well. Coaxial connectors use transverse electromagnetic (TEM) propagation which is not affected by dispersion and, because of the DC start frequency of the coaxial interface, biasing or conducting a DC signal is not an issue.

Time Domain Advantages

Another positive advantage of the broadband nature of coaxial connectors with a start frequency of DC is all time domain measurements can be accomplished. Low pass time domain and eye diagrams can be tested with even better resolution as the frequency moves to 100 GHz and beyond. This type of evaluation is necessary for many high-speed applications because an eye diagram or impedance graph provides insight into signal integrity of the interface (Figure 8).

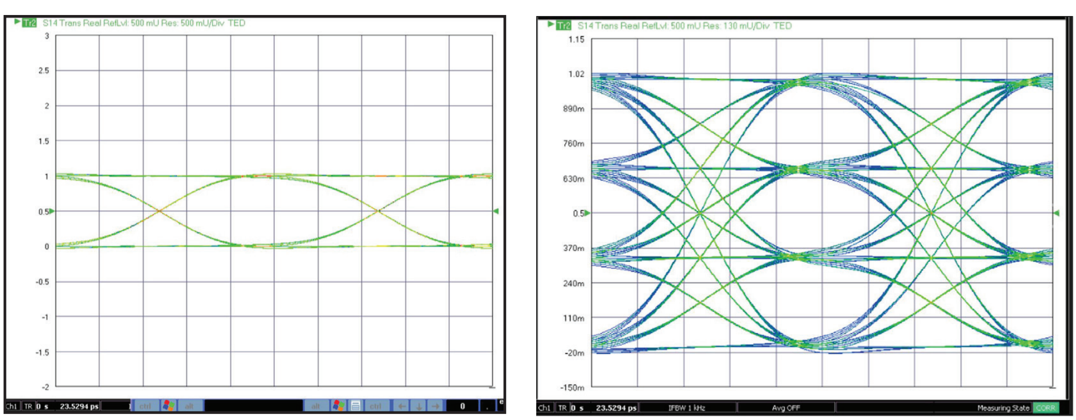


Figure 8. Simulated 90 Gbps NRZ and PAM4 Eye Diagrams

Measurement Setup Advantages

Most test and measurement equipment have a native coaxial interface. The advantage a coaxial interface is the direct connection between interfaces. There is no need for alignment screws and guide pins. Issues of repeatability are removed with a coaxial interface as there is only one way to connect and, with the use of a proper torque wench, measurements can be carried out over and over again with correlating results.

Performance

Waveguides are a nearly lossless conductor of signals and that is a plus, but with advances in coaxial connector manufacturing and design, insertion losses can be managed to be quite low. For 0.8 mm adapters, insertion losses of 0.7 dB (typical) can be achieved (Figure 9).

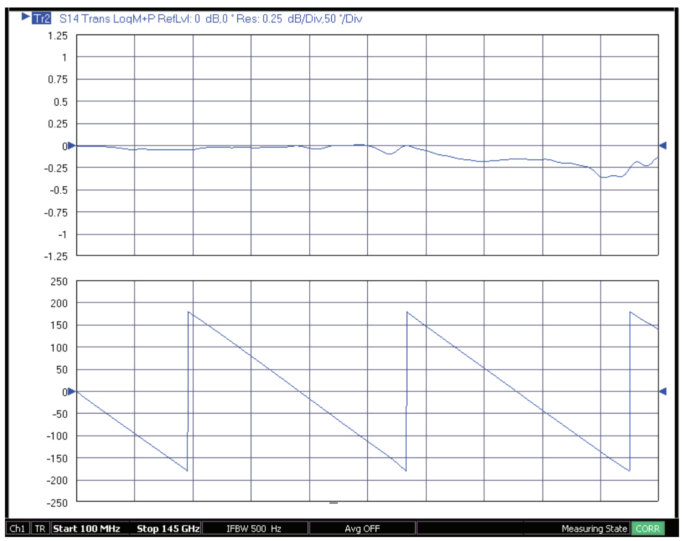


Figure 9. Insertion Loss and Phase Plot of an Anritsu 33.8F.8F50 0.8 mm Adapter

What is Available in Market for Millimeter-Wave Coaxial Connectors?

Figure 10. 0.8 mm Spark Plug Connectors

Anritsu has product offerings for both W1 (1.00 mm) and 0.8 mm connectors. These connectors are precision connectors (Figure 10) that offer the best quality and performance for automotive radar, 5G mmWave, 6G mmWave development and R&D, defense and aerospace, and many other applications that will exceed 100 GHz. These connectors can be used in conjunction with Anritsu components and test equipment.

Anritsu not only offers a line of connectors up to 145 GHz, Anritsu also has the largest selection of W1 110 GHz components in the industry (Figure 11). These components can help customers improve measurements over waveguide equivalent components by adding ease of use, repeatability and frequency scalability.

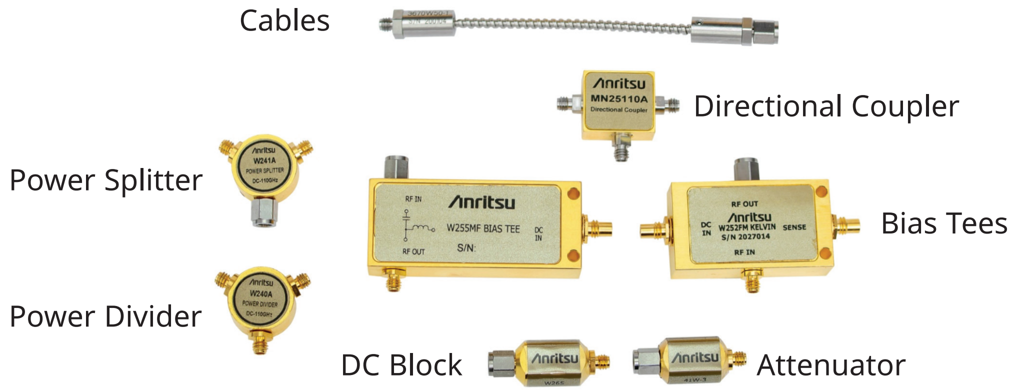


Figure 11. Anritsu 110 GHz Components

Anritsu also has test and measurement equipment that can help support manufacturers that need to move to coaxial connectors for frequency coverage above 100 GHz (Figure 12). VectorStar VNAs cover low frequency, 70 kHz to up to 220 GHz, and are compatible with 0.8 mm connectors. Likewise, VectorStar has both a 110 GHz and 145 GHz option VNA and can support W1 (1.00 mm) as well as 0.8 mm connectors.

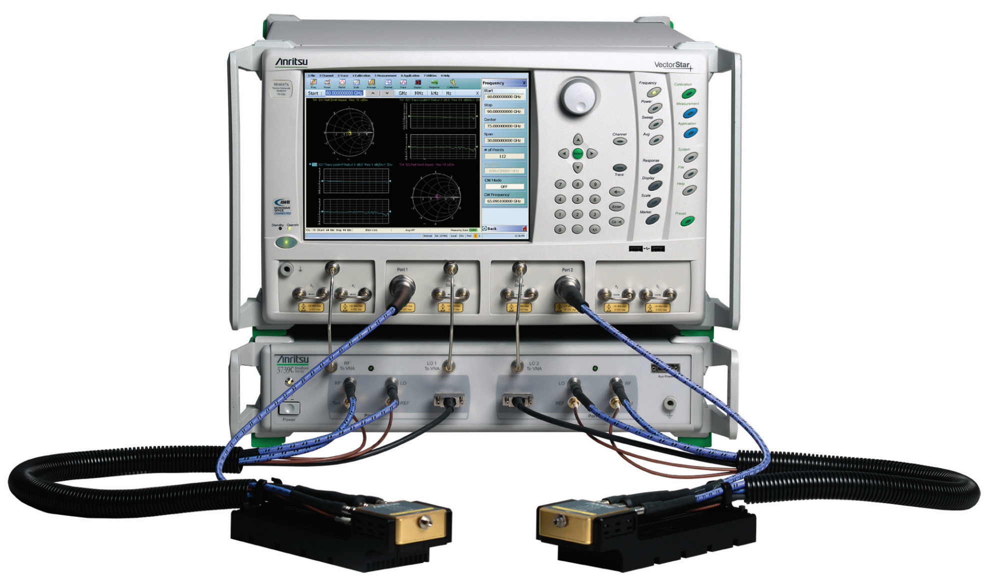


Figure 12. VectorStar ME7838 Vector Network Analyzer

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2. IEEE Instrumentation and Measurement Society. IEEE Standard for Precision Coaxial Connectors (DC to 110 GHz). New York, NY: Office Headquarters. 2007.

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11410-02836 Rev. A Printed in United States 2020-09