Making Millimeter-Wave Technology More Accessible

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Abstract:

The Millimeter-wave spectrum generally refers to the frequency range of 30 to 300 GHz. In recent decades it has found wide application in space, aviation, military, science, industrial, commercial and consumer systems due to its unique wavelength characteristics. It is not a new technology, although it is still considered by many to be an expensive technology because of historically high entry barriers. Advancements in semiconductor devices, packaging, and manufacturing techniques have been slow to change this attitude. To a large degree the mm-wave electronics industry continues to favor custom solutions rather than adopting more of the prototyping and manufacturing approaches that have successfully reduced hardware costs at lower frequencies. To overcome these historical barriers to new applications, the mm-wave industry is increasingly turning to standard component packages and new RF interfaces that provide alternatives to traditional coaxial and waveguide connections. Improvements in test and measurement techniques have also lowered some of the hurdles that impeded mm-wave hardware development. This article reviews significant improvements in the areas of commercial off-the-shelf (COTS) mm-wave components, novel waveguide connectors for lower-cost packaging, and contactless waveguide flanges that can streamline the measurement of waveguide components. These achievements have

accelerated the development of new mm-wave systems while reducing the cost of transitioning to higher rates of production. As a result, mm-wave technology is much more accessible and more affordable for new applications.

Keywords: Millimeter-wave, Components, Waveguide Connectors, Contactless Flanges, Vector Network Analyzers, Extenders, Calibration Kits, Testing

Introduction

The mm-wave spectrum has significant advantages over its lower-frequency RF and microwave counterparts. Widely accepted to comprise 30 to 300 GHz, this frequency range offers smaller wavelengths and wider bandwidths. These features have specific advantages. Smaller wavelengths are attractive because they allow users to take advantage of additional electromagnetic spectrum. Also, for a given antenna aperture size, smaller wavelengths enable narrower beams to improve the angular resolution of radar systems used in weapons, guidance systems, aircraft, and remote-sensing satellites. Wider bandwidths support higher data rates in communications systems and improve distance resolution for target identification in radar systems. Increased bandwidth can also improve the sensitivity and resolution of passive imaging systems, as well as provide systems with greater immunity from jamming and other interference [1], [2], [3], [4]. Despite these advantages mm-wave technology is often seen as too expensive or impractical for many new applications.

Until recently the mm-wave frequency spectrum was mainly used for military, aerospace, and scientific research applications. It has been generally limited to weapon guidance, seekers, radars, military communication equipment, remote control, remote sensing, radiometry, radio telescopes, material science, and other areas of research and development. In recent years, technological advances — especially those related to simulation and design tools, semiconductor device performance, and manufacturing methods — have allowed mm-wave technologies up to 170 GHz to reach their current stages of maturity [5], [6], [7].

As mm-wave technology continues to find increasing opportunities in traditional markets, potentially explosive opportunities are seen in a wide range of new applications. There is increasing interest in topics such as improved internet connectivity, enhanced safety and security, as well as “smart” cities, homes, and appliances. As a result, mm-wave technology may experience vastly more growth in new commercial and consumer-oriented applications. Research and development is growing in many areas including the Internet of Things (IoT), high data-rate communication, passive imaging, transportation safety and management, driverless cars, security systems, commercial satellites, and test/measurement equipment. This activity confirms that the mm-wave electronics industry is healthy and growing [8], [9], [10], [11].

As the opportunities for mm-wave technologies have grown, the technical and business landscapes have often been difficult to navigate due to a lack of manufacturing standards and few stable building blocks for system integration. Reasons for not having standard building blocks in the industry include the limited bandwidths that are typically achieved using traditional design approaches. This has resulted in the continued need for customization to cover specific frequency ranges. Further, complex interconnections between building blocks can limit system performance due to high insertion loss or poor impedance matching. At higher mm-wave frequencies approaching 300 GHz, waveguide sections with low insertion loss are costly to produce. These and other factors have made the industry reluctant to develop standard building blocks. Instead, many developers of mm-wave hardware continue to favor customized design approaches. Revolutionary packaging and testing technologies are needed to speed up the development process and reduce prototyping costs so that new applications can be demonstrated and implemented as quickly as possible.

Historical Considerations

Traditionally, mm-wave hardware development required a large amount of design activity at the component level. An advanced Engineering degree with considerable training in electromagnetic theory and network analysis were commonly regarded as prerequisites for entering the field of microwave and mm-wave component design. Furthermore, the machinery required to make precision mechanical parts for mm-components was lacking while machinists with the necessary skills were limited. Experienced, hands-on technicians required many years practice to develop the “know-how” needed to compensate for imperfect designs and machining tolerances. In recent years the emergence of advanced design software has greatly reduced the need to apply electromagnetic theory and network analysis methods to the development of mm-wave components and systems. Meanwhile advanced mechanical design software such as Solidworks, as well as improved CNC machinery, have helped to reduce the need for highly experienced manufacturing personnel, improved mechanical parts accuracy, and eliminated “skill” dependency tremendously.

Now, the need to design systems at the component level is being reduced by the increased availability of COTS hardware. System developers can thus focus more of their efforts on building proof-of-concept prototypes and pre-production systems. As a result, it is increasingly possible to evaluate new applications faster and study their economic feasibility with lower up-front investment.

Another common barrier to entry for mm-wave product development is the need for advanced test equipment. Basic instrumentation includes signal generators, amplifiers, signal analyzers, and network analyzers. Traditionally such equipment was expensive to purchase and maintain, and much of it required special training and skills for proper operation. In recent years the cost of test equipment has declined significantly, but it still represents a major investment for anyone seeking to harness mm-wave technology.

For advanced instruments such as Vector Network Analyzers (VNAs), especially those operating at mm-wave frequencies, high levels of operator training have been essential to achieve reliable measurement results. Further, slow test procedures have limited the number of devices that could be tested over a given time period. Recent advancements in VNA test equipment are making it easier to perform component tests, allowing test equipment to pay for itself sooner due to increased productivity and lower operating costs.

Choosing Suppliers

For those involved in the development of mm-wave systems for new applications, some of the more difficult challenges include surveying and selecting component suppliers. This is especially true in systems where one component can impact the performance of several others. Moreover, the depth and breadth of a supplier's understanding of these dependencies must be discovered as soon as possible to ensure that integrated systems can achieve the best possible performance. For many years Eravant, formerly SAGE Millimeter (Torrance, CA), has been investing heavily to build up its standard modular products, encompassing a wide range of broadband coaxial and waveguide components with focus on mm-wave bands from 30 to 325 GHz. These standard modules are generally designed to cover full waveguide bandwidths, or bandwidths that are as wide as possible using available technologies.

Some standard models span multiple octave bandwidths. For example, amplifier model SBB-0117033015-VFVF-E3 covers 10 MHz to 70 GHz with 30-dB nominal gain and +15 dBm output power at 1-dB compression. The broadband nature of Eravant's standard modules offers opportunities for system integrators to find suitable building blocks that meet their system requirements without paying for non-recurringengineering (NRE) and waiting for someone to address their particular frequency range. Eravant's standard COTS product categories cover almost everything needed to develop mm-wave wireless systems.

Eravant has also introduced a series of novel waveguide connectors under the trademarked name, "Uni-Guide". This product line offers an RF interface concept that is similar to coaxial connectors. The Uni-Guide™ connector series is offered to the mm-wave component and subsystem industry to reduce the need for customized device packages, and to shorten development and manufacturing cycle times [12].

In mm-wave frequency bands, rectangular waveguide is the most common transmission-line medium due to its low loss and high power capacity. Unlike coaxial cables, waveguide connections are rigid as well as polarized. As a result, custom waveguide port locations and orientations are frequently desired for system integration purposes. In addition, hermetically sealed waveguide windows are often needed. Such windows are difficult to implement and expensive to produce [13]. Alternatively, a Uni-Guide™ waveguide connector can preserve the hermetic seal of a component package if standard glass beads are used for RF port sealing.

The Uni-Guide™ waveguide connector series can also help to minimize packaging inventories, as well as simplify inventory management. Component manufacturing costs are lowered by using standard housings that were already developed for coaxial connectors. As a result, the waveguide connector is expected to be a revolutionary package technology that eliminates many custom-designed packages while reducing product development cycle times and lowering design and production costs.

Test Challenges

Testing waveguide components and systems has always been challenging. Any misalignment, small gap, or excessive mechanical tolerance in waveguide connections can lead to inaccurate system calibration, time-consuming adjustments, and redundant efforts. There are many research papers and application notes that address these topics [15], [16], [17]. To increase testing and calibration speeds, as well as improve overall repeatability, Eravant developed the Proxi-Flange™ contactless waveguide flange and the WaveGlide™ rail positioning system. These innovations greatly improve the productivity and reliability of mm-wave test systems [18]. Additionally, lower-cost mm-wave VNA frequency extenders and calibration kits are available to further lower the cost barriers for new and budget-limited system developers.

Millimeter-wave System Configuration

Communication and radar systems tend to include a variety of component types in their functional block diagrams. Antennas, antenna feed networks, amplifiers, up-converters, down-converters, control devices, oscillators, filters, diplexers, power distribution networks, and interconnection products are commonly used. Figure 1 shows the block diagram for a typical microwave or mm-wave communication system front end. Various common components, i.e., building blocks or modules, are included. These functional modules are largely available from the Eravant website as standard

COTS products covering frequencies up to 220 GHz, with an increasing number of component selections available for frequencies approaching 325 GHz.

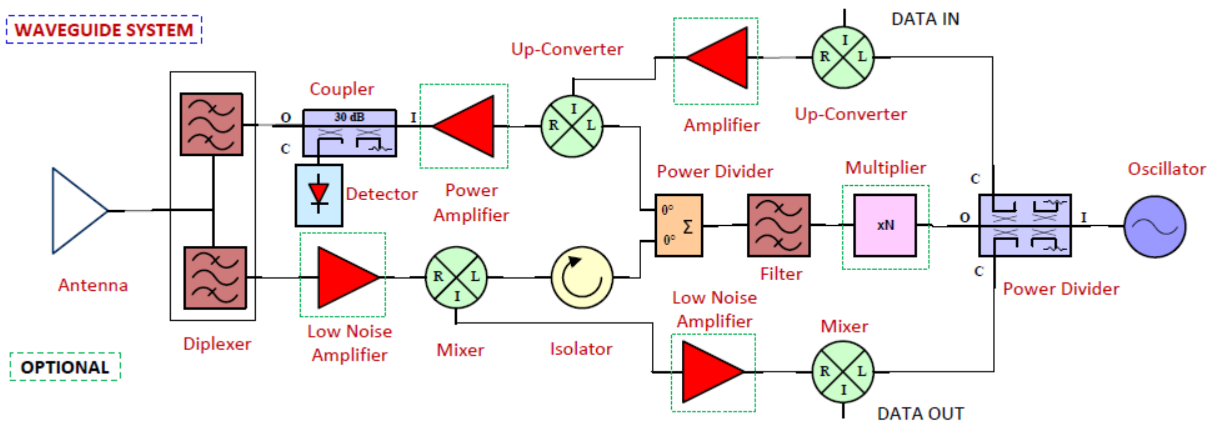

Figure 1 – Typical communication front-end block diagram

Eravant's large pool of standard products, as well as its extensive design library and established manufacturing processes, support the rapid development of customized modules by altering or updating standard models at a fraction of the usual costs and

Figure 2 – E-Band subsystem constructed using COTS modules

lead times. This design approach speeds up system development, reduces the realization cycle time, and lowers overall program costs. Further, these products are readily configured with standard waveguide interfaces for direct connections to other components. Additional interconnection devices, such as adapters and transitions, as well as waveguide components including straights, bends and twists, may be eliminated when individual modules are offered with more configuration options.

With approximately 5,000 COTS models, Eravant stands ready to support rapid system concept demonstration, scientific apparatus development, test-lab tooling, as well as a variety of instrumentation needs. All of Eravant's products are designed and manufactured using rigorous processes. Many are readily qualified for space and military applications after the required environmental testing is performed.

Signal Sources

Clean and stable signal sources are critical building blocks in radar and communication systems. Tuning bandwidth, tuning speed, phase noise, harmonic content, spurious levels, and frequency stability are primary considerations that often determine overall system performance. Since its beginning, Eravant has been a leader in the production of low-noise, free-running mm-wave Gunn oscillators. Their economy and excellent phase-noise performance make them ideal signal sources in many applications. Law-enforcement radar, speed sensors and security systems are a few of the main focuses of this product line. With output frequencies available from 9 to 110 GHz, mechanical tuning ranges are as wide as +/- 12 percent at various output levels.

For example, a 35-GHz fixed-tuned Gunn oscillator delivers +12 dBm output power with phase noise of -95 dBc/Hz at a frequency offset of 100 kHz (Fig. 3). Frequency stability is -0.3 MHz/°C. Another example is a 90-GHz mechanically tuned oscillator that operates with +16 dBm output power and +/- 2.0 GHz tuning bandwidth. These cost-effective oscillators can be tuned within the range of 30 to 38 GHz or 90 to 100 GHz. Options include bias-voltage tuning and higher output power to meet the needs of various applications.

Voltage-tuned Gunn oscillators are widely used in range/speed radar sensors and in frequency-agile systems. They achieve industry-leading value and performance across the 9 to 96 GHz spectrum.

Figure 3A – 35 GHz low cost fixed-tuned Gunn oscillator (SOL-35312-28-G1)

Figure 3B – 90 GHz mechanically tuned Gunn oscillator (SOM-90304316-10-M1)

Free-running oscillators with greater frequency stability are often required in applications such as semiconductor reliability testing and qualification. Such signal sources are typically realized using dielectric-resonator oscillators (DROs). Sources with precision frequency stability are offered as fixed-frequency Phase-Locked Dielectric Resonator Oscillators (PLDROs) or as wide-band frequency synthesizers. Both oscillator types can be locked to either an internal crystal oscillator or a more stable high-performance external clock such as a GPS frequency reference. Basic DRO and PLDRO models cover the frequency range of 3 to 40 GHz, with nominal output power of +10 to +20 dBm.

Standard frequency synthesizer modules can be tuned from 0.1 to 10 GHz or 0.2 to 20 GHz with 10-kHz frequency resolution. Models configured for high-speed tuning can achieve settling times of 3 microseconds. These oscillators use a coaxial connector for the RF output port. Sources with higher frequency or higher output power can be achieved by adding frequency multipliers and amplifiers. DROs, PLDROs, and frequency synthesizers can be hermetically sealed and can cover wide temperature ranges to meet aerospace and millitary standards (Figure 4).

Figure 4A – 22 GHz free-running DRO model SOD-22301215-SF-S1

Figure 4B – 28 GHz phase-locked DRO, model SOP-28310113-KF-BB

Figure 4C – 0.2 to 20 GHz high-speed synthesizer, model SOT-02220313200-SF-B6

With add-on frequency multipliers, these oscillators can readily reach 220 GHz.

Frequency Multipliers

Frequency multipliers are often used to achieve higher operating frequencies. Both passive and active frequency multipliers are available. Passive multipliers typically employ a Schottky diode and generally use multiplication factors of 2, 3, or 4. They can provide frequency coverage over full waveguide bands up to 220 GHz. Passive multipliers require no DC power and have relatively straightforward implementations, but they exhibit significant conversion loss. In contrast, active multipliers combine passive multiplier circuits, filters and amplifiers to provide higher output power and higher multiplication factors. Most of Eravant's active frequency multipliers can cover full waveguide bandwidths. Alternatively, units with narrower frequency coverage can be designed to reach other performance goals.

One of the consequences of frequency multiplications is that noise sidebands contained in the primary signal are also multiplied, and are extended to higher offset frequencies. The carrier-to-noise ratio at a given offset frequency is degraded by 20 Log(N), where N is the multiplication factor. Harmonic and sub-harmonic content may also be a consideration. To minimize these effects, innovative circuit designs and rigorous manufacturing processes are incorporated into Eravant's high-performance frequency multipliers (Figure 5).

Figure 5A – 110 to 170 GHz passive X2 multiplier, model SFP-06212-S2

Figure 5B – 75 to 110 GHz active X6 multiplier, model SFA-753114616-10SF-E1

Frequency Converters

Frequency converters are key functional blocks in most microwave and mm-wave systems. They typically translate the spectrum of an input signal from an Intermediate Frequency (IF) to a Radio Frequency (RF), or vice-versa. Eravant's frequency converters support IF signals from DC to 40 GHz using Local Oscillator (LO) and RF frequencies spanning 18 to 220 GHz. Frequency converters are often referred to as "mixers". Converter types include Fundamental (balanced), Subharmonically Pumped (LO ≈ 1/2 RF), Harmonic, Quadrature, Image-Reject, and Single-Sideband (SSB). Frequency converters are also categorized as biased or non-biased. The choice usually depends on the system frequency plan and the available DC power budget.

For example, Eravant's W-band mixer family includes a non-biased balanced fundamental mixer, model SFB-10-N1, that covers the RF/LO frequency range of 75 to 110 GHz with an IF frequency range of DC to 40 GHz (Figure 6A). The mixer requires +13 dBm LO power, which can be difficult or costly to obtain at higher mm-wave frequencies. As an alternative, an externally biased converter, SFB-10-E2, requires LO power of 0 dBm. A subharmonically pumped converter (Figure 6B), model SFS-

90311415-102FSF-N3, may be used with LO signals from a lower-frequency source that is chosen for performance or cost considerations. A possible motivation for using a subharmonically pumped mixer is to double the frequency separation between the source's Fundamental and Spurious outputs by a factor of two. This result can ease the filtering of unwanted harmonic and spurious content. A quadrature mixer, model SFQ-75311415-1010SF-N1-M, can be configured for single-side-band rejection or for various modulation schemes (Figure 6C). By adding an external IF hybrid circuit, an image-reject mixer can be configured for communication and radar applications without using the more costly approach of incorporating two balanced mixers, a hybrid coupler, and a power combiner. The quadrature mixer approach can effectively reject spurious signals when the IF is low or is very close to the carrier frequency. Harmonic mixers such as model numbers SFH-06SFSF-A3 and STH-10SF-S1 are available for expanding the frequency range of spectrum analyzers to the W band 75 to 110 GHz and D band 110 to 170 GHz, respectively, when system performance testing is required (Figures 6D and 6E).

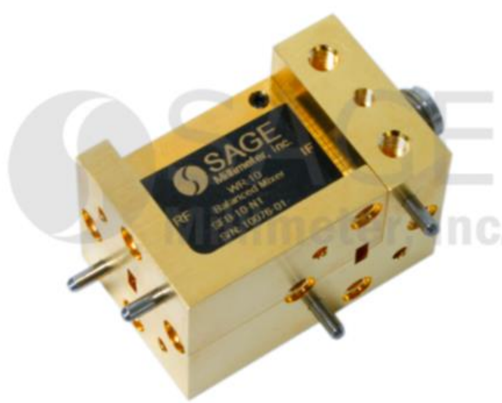

Figure 6A, 75 to 110 GHz non-biased balanced mixer (SFB-10-N1)

Figure 6B, 90 to 110 GHz subharmonically pumped mixer (SFS-90311415-102FSF-N3)

Figure 6C, 75 to 110 GHz quadrature (I/Q) mixer (SFQ-75311415-1010SF-N1-M)

Figure 6D, 110 to 170 GHz harmonic mixer (SFH-06SFSF-A3)

Figure 6E, 75 to 110 GHz spectrum analyzer mixer (STH-10SF-S1)

Design considerations for mm-wave up-converters are similar to those encountered with down-converters, i.e. when using the IF port as the input and the RF port as the output. For double-sided and single-sideband modulator applications, system considerations are similar to those encountered when mixers are used as up-converters. However, modulators generally use the IF port for the modulation input, while the LO and RF ports are used for the unmodulated input and modulated output signals, respectively. The modulation signal usually requires relatively high power, typically +16 dBm, to fully bias diodes or other modulation devices. The LO port is typically fed with smaller signal, such as -20 dBm or lower.

Amplifiers

Amplifiers are essential functional blocks that make up or compensate for signal loss. They are also used to increase signal levels during transmit and receive processes. Three types of amplifiers are typically encountered. They include power amplifiers, low-noise amplifiers, and general-purpose gain blocks. Eravant designs and manufactures its amplifiers to cover full-waveguide bandwidths, or bandwidths that are as wide as possible, as the first priority. This allows COTS products to accommodate as many applications as possible. When wide bandwidth is not supported by the available technology, an application-specific bandwidth may be chosen. For general-purpose gain blocks, ultra-broad bandwidth is the main focus so that a limited number of models can support a majority of developmental programs and application needs.

Currently, low noise amplifiers cover the frequency range of several GHz up to 270 GHz. In a WR-03 waveguide package, model SBL-2242741585-0303-E1 provides 15-dB gain with 8.5-dB noise figure from 220 to 270 GHz (Figure 7A). A full-band amplifier, model SBL-1141743065-0606-E1, provides 30-dB gain from 110 to 170 GHz with 6.5-dB noise figure (Figure 7B).

Figure 7A. WR-03 low noise amplifier

Figure 7B. 110 to 170 GHz low noise amplifier

Power amplifiers typically incorporate GaAs, InP or GaN semiconductor technologies. Power combining techniques in planar circuits and in waveguide configurations are utilized to achieve the best electrical and mechanical performance. The frequency range of Eravant's power amplifier family is 2 to 110 GHz. An E-Band model spans 71 to 76 and 81 to 86 GHz for last-mile applications (Figure 7C). A Ka-Band model can be used in 35-GHz radar systems (Figure 7D). The highest linear output power delivered from the E-band power amplifier is 1.5 Watts. The Ka-band power amplifier yields 10 Watts of output power at saturation.

Figure 7C. E-Band power amplifier

Figure 7D. Ka Band power amplifier

The third amplifier family comprises broadband gain blocks. The focus of these amplifiers is to offer moderate output power and maximum bandwidth for system gain boosting. Examples include coaxial amplifiers that operate from 10 MHz up to 70 GHz. They are offered as standard models to satisfy many system applications. Figure 7E shows model SBB-0117033015-VFVF-E3. It provides 30-dB small signal gain and 15-dBm

P-1 dB output power from 10 MHz to 70 GHz with a typical noise figure of 6.0 dB. A companion model with lower gain is also available as a COTS option.

Figure 7E. 10 MHz to 70 GHz Broadband Amplifier

While configuring the standard amplifier models, two gain levels are considered for system applications, namely, the intermediate gain range of 15 to 20 dB and the higher gain range 30 to 35 dB. Other gain values can be readily configured using these standard gain values. All amplifiers are designed and manufactured with integrated voltage regulators and a single DC power input to reduce system integration complexity.

Control Devices

Control devices are typically employed in systems where control of the signal's amplitude, phase or destination is required. The three most common control devices include attenuators, phase shifters and switches. Standard units fulfill control functions in the frequency range of 0.5 to 110 GHz.

The switch family includes electrical, mechanical, and electro-mechanical types configured as single-pole and multiple-pole models. A SPDT switch, model SKD-5031146025-1F1F-R1-M, covers the frequency range of 50 to 110 GHz using 1-mm connectors for its RF ports. Waveguide-interfaced models are available to cover major mm-wave bands in the 0.5 to 43 GHz frequency range for 5G applications. Figures 8A and 8B show typical examples. Electrical switches based on PIN diodes can provide fast switching times. Mechanical and electro-mechanical models are suitable for applications that require higher port isolation and lower insertion loss. Examples include models SWJ-28-M1-H (22 to 44 GHz) and SWJ-10-TS (75 to 110 GHz). They are shown in Figures 8C and 8D.

Figure 8A. A SPDT Switch operates from 50 to 110 GHz using 1 mm coaxial connectors

Figure 8B. A SP4T switch covers the 5G FR2 bands up to 43 GHz

Figure 8C. Model SWJ-28-M1-H is a DPDT mechanical switch that covers the 5G FR2

band, 24 to 43 GHz

Figure 8D. Model SWJ-10-TS is an electro-mechanical DPDT switch that operates

from 75 to 110 GHz

Similarly there are three types of attenuators, namely electrical, mechanical, and electro-mechanical. Electrical attenuators employ PIN diodes or pHEMT devices to achieve high-speed amplitude control with moderate insertion loss and good isolation performance. Other models provide low insertion loss and high attenuation. Figures 8E, 8F, and 8G show examples of V-band attenuators. They include electric, fixed, and level-setting waveguide types. Direct reading and programmable attenuators belong to the test and measurement categories (Figures 8H and 8I). The entire attenuator family covers frequencies up to 325 GHz. The majority of attenuator products serve either a full waveguide bandwidth or an application-specific bandwidth. Electrically tunable attenuators have tuning speeds on the order of 100 ns. While the electrical tunable versions focus on tuning speed, manual or electro-mechanical tunable versions can reach attenuation values up to 60 dB with low minimum insertion loss.

Figure 8E. Attenuator model SKA-5037533030-1515-A1 supports full V-Band operation

Figure 8F. A V-Band fixed waveguide attenuator

Figure 8G. A V-Band level-setting waveguide attenuator

Figure 8H. A V-Band direct-reading attenuator, model STA-60-15-D5

Figure 8I. Programmable attenuator STA-60-15-P1 spans 50 to 75 GHz

The phase shifter is another important component in many microwave and mm-wave systems. Electrically and mechanically tuned phase shifters can be found in many test labs. Examples are shown in Figures 8J and 8K. Operating frequencies for standard phase shifters extend to 170 GHz.

Figure 8J. A digitally controlled electrical phase shifter covers 6 to 18 GHz

Figure 8K. A WR-15 mechanically adjustable phase shifter operates from 50 to 75 GHz

Other control devices such as power limiters are also developed and manufactured as COTS components.

Ferrite Devices

Ferrite non-reciprocal devices are widely used in microwave and mm-wave systems to provide port isolation or to control signal flow. Isolators are two-port devices that are mainly used for port impedance matching improvement or to guide signals in a certain direction. Circulators can be used for either port isolation or for signal duplexing. Faraday rotation isolators can generally cover full waveguide bandwidths with high levels of isolation. Junction isolators and circulators offer lighter weight and more compact size. Although junction isolators and circulators are typically optimized for specific bandwidths, recent progress has advanced some junction isolators and circulators to cover full waveguide bands in WR-42, WR-34 and WR-28 with somewhat compromised performance degradation, such as slightly higher insertion loss and lower isolation at the band edges. Figures 9A, 9B and 9C show a G-Band Faraday isolator, a W-Band narrow-bandwidth junction circulator, and a Ka-Band full waveguide band junction circulator, respectively.

A number of coaxial ferrite devices are also offered as COTS products. The frequency coverage of ferrite devices is from 8.2 to 220 GHz over specific bandwidths. Recent progress has been made to miniaturize Faraday rotation isolators. Currently, compact and miniature Faraday isolators are offered as COTS products that cover operating frequencies up to 220 GHz. Their smaller size can enhance system integrations. Figure 9D shows a G-Band miniature Faraday isolator that spans 140 to 220 GHz with 4-dB typical insertion loss and better than 20-dB isolation, with a physical length just over one-half inch.

Figure 9A. A G-Band Faraday isolator covers 140 to 220 GHz

Figure 9B. A W-Band junction circulator targets 92 to 98 GHz

Figure 9C. A Ka-Band, full waveguide band circulator spans 26.5 to 40 GHz

Figure 9D. A G-Band miniature Faraday isolator covers 140 to 220 GHz

Antennas

For any wireless system, antennas have a major impact on overall performance. With advanced signal-processing methods, multiple signal paths can be embraced to achieve greater system capacity and functionality. However, more traditional systems benefit from having antennas with good polarization purity and limited side-lobe responses. Eravant carries many rectangular and circular horn antennas (Figures 10A and 10B). Horn antennas support applications from radar and communication systems to advanced test instrumentation. With phase error corrections, lens-corrected horns provide enhanced performance (Figure 10C). Scalar horns and choke flange horns offer lower side lobes compared to other alternatives. They also provide nearly equal beam widths in their E and H planes, along with high cross-polarization rejection. Selected models are shown in Figures 10D and 10E. Higher gain and narrower beam widths are realized using Gaussian optics antennas (Figure 10F) and Cassegrain antennas (Figure 10G). They can serve in applications operating from several GHz up to 325 GHz.

Figure 10A. Rectangular Horn Antenna, WR-12 Band

Figure 10B, Circular Horn Antenna, WR-15 Band

Figure 10C. Lens Correct Horn Antenna, WR-10 Band

Figure 10D. Scalar Horn Antenna for WR-28 Band

Figure 10E. Choke Flange Antenna for WR-12 Band

Figure 10F. Gaussian Optical Lens Antenna, WR-06 Band

Figure 10G. Cassegrain Antenna, WR-22 Band

Dual-polarized antennas are often needed in radar and communication systems, test and measurement systems, and antenna ranges. They can be used as duplexing antennas when dealing with separate Transmit and Receive signals, or with circularly polarized signals. Dual polarized antennas are also convenient when performing antenna tests where test signals having either vertical or horizontal linear polarization are both desired. The antenna polarization is selected through switches, eliminating the need to physically rotate the Transmit or Reference antenna. The arrangement avoids time-consuming setup procedures and possible measurement errors caused by misalignment of the source antenna and the DUT. Additionally, circularly polarized signals can be transmitted by simultaneously exciting the Vertical and Horizontal antenna ports using the appropriate offsets for phase and amplitude.

There are two common ways to construct dual polarized antennas. Examples of quad-ridge antennas, and antennas employing ortho-mode transducers (OMTs), are shown in Figures 11A, 11B, 11C, 11D, and 11E.

Figure 11A. Quad Ridge Horn for the 5G FR2 Band, 6 to 44 GHz

Quad-ridge antennas use tapered-slot or Vivaldi-like antenna apertures. Two such apertures are co-located at right angles to each other to yield separate Vertical and Horizontal polarization ports, usually employing coaxial connectors. Alternatively, a waveguide horn is often paired with an OMT to realize a dual-polarized antenna. The horn antenna may have either a rectangular or circular feed. Examples of standard OMT based dual polarized antennas are shown in Figures 11D and 11E. Other configurations can support separate right-hand and left-hand circular polarizations without requiring additional engineering efforts. OMT-based antennas typically offer higher cross-polarization rejection, higher port isolation, flatter gain, well-defined beam shapes, or lower side lobes when compared with quad-ridge antennas.

Figure 11B. A quad-ridge horn operates from 4 to 24 GHz

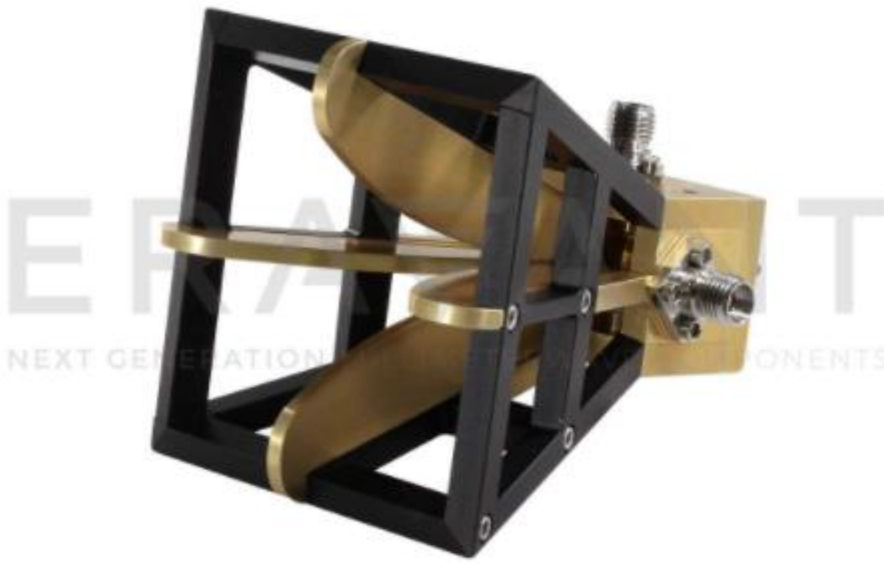

Figure 11C. Model SAV-0434031428-KF-U5-QR spans 4 to 40 GHz

Figure 11D. Model SAH-2434231060-328-S1-280-DP operates from 24 to 42 GHz

Figure 11E. Model SAF-7531141340-110-S1-100-DP covers 75 to 110 GHz

The pros and cons of these antenna types are summarized in Table 1. In general, quad-ridge antennas cover broader operating bandwidths, often more than an octave, such as 2 to 18 GHz or 4 to 24 GHz. They are limited to the lower or middle mm-wave frequency bands due to stringent machining and assembly boundaries. The main drawback of OMT-based antennas is their operating bandwidths, being limited to standard waveguide operating bandwidths generally.

Table 1. Dual Polarized Antenna Comparison

Item	**Quad-Ridge Antenna**	**OMT-Based Antenna**
Antenna Type	Circular or rectangular horn	All types
Operating Bandwidth	Ultra-broad, such as 2 to 18 GHz	Waveguide bandwidths in general
Gain	Low, 10 to 20 dBi typically	Wide range, 10 to 50 dBi
Side Lobe Levels	High, 10 to 20 dB	Wide range, antenna type dependent

Beam Width	Limited range	Wide range, antenna type dependent
Cross-Polarization	Low, 25 dB typical	High, 70 dB typical
Port Isolation	Low, 20 dB typical	High, 40 dB typical
Port Type	Coaxial	Waveguide or Coaxial

Because of the performance limitations of quad-ridge dual polarized antennas, OMT based antennas are used in more applications. By selecting among various antenna types, such as the conical horn, pyramid horn, probe antenna, lens-corrected horn, scalar horn, choke flange horn, Gaussian antenna or a dish, a variety of dual polarized antennas can be configured with OMTs. However the antenna port of standard OMTs is configured with square waveguide. To make a connection between an OMT and an antenna with a circular waveguide feed, a mode transition is required. Table 2 summarizes the range of OMT-based antennas to illustrate how various OMT-based dual polarized antennas can be readily configured using standard COTS components.

Table 2. OMT-Based Dual Polarized Antennas Overview

Dual Polarized Antenna Types	**Features**
OMT + Conical Horn (SAC Series)	Full waveguide band performance, gain is limited to 25 dBi, high side lobe level, lower cost
OMT + Pyramid Horn (SAR Series)	Full waveguide band performance, gain is limited to 25 dBi, high side lobe level, lower cost
OMT + Choke Flange Horn (SAH Series)	Full waveguide band performance, broader beamwidth and low gain, low side lobe level, lower cross-polarization, moderate cost
OMT + Scalar Feed Horn (SAF Series)	Full waveguide band performance, broader beamwidth and gain up to 17 dBi, low side lobe level, lower cross-polarization, moderate cost
OMT + Lens Corrected Horn (SAL Series)	Full waveguide band performance, narrow beamwidth and high gain depending on the dish size selection, low side lobes, moderate cost
OMT + Gaussian Antenna (SAG Series)	Full waveguide band performance, narrow beamwidth and high gain depending on the aperture size selection, low side lobes, lower cross-polarization, high cost
OMT + Cassegrain Antenna (SAY Series)	Full waveguide band performance, narrow beamwidth and high gain depending on the dish size selected, lower cross-polarization, high cost

OMTs are not only used as key antenna feed elements. They are also the key duplexing component in many Radar and communication systems that transmit and receive signals with high isolation. Cross-polarized transmit and receive signals enable full-duplex communication through a single antenna with very low coupling between channels. Although other duplexing devices such as Transmit/Receive (T/R) switches and ferrite circulators are commonly employed as duplexers, OMTs often result in the best performance overall in terms of operating bandwidth, insertion loss and isolation. Recognizing this potential, Eravant supplies OMTs with some of the best performance metrics available, including 40-dB port isolation and high levels of cross-polarization suppression. The OMT family covers the frequency range of 7 to 220 GHz in 15 waveguide bands, namely, WR-112 to WR-05. The OMTs support full waveguide band operation, with some covering wider bandwidths for specific applications. Figures 11F and 11G illustrate two popular OMT models for Ka-band 5G mm-wave FR2 applications, and for E-Band last-mile and automotive radar applications. The Ka-band model works beyond the WR-28 waveguide operating bandwidth, covering the frequency range of 23 to 44 GHz. The E-Band OMT spans 60 to 90 GHz to encompass the last-mile frequency bands of 71 to 76 GHz and 81 to 86 GHz.

Figure 11F, Model SAT-343-28028-S1 OMT for the 23 to 44 GHz band

Figure 11G. Model SAT-FE-12212-S1 OMT operates from 60 to 90 GHz

Omnidirectional antennas are often found where the landscape requires uniform signal coverage. Offering gains from 2 to 7.5 dBi, COTS passive omnidirectional antennas cover full waveguide bands between 26.5 and 140 GHz. Models SAO-2734030810-28-S1 and SAO-7531140230-10-S1 are presented in Figures 12A and 12B, respectively.

Figure 12A. An omni-directional antenna covers 26.5 to 40 GHz with 10-degree beam width

Figure 12A. An omni-directional antenna spans 75 to 110 GHz with 30 degree beam width

Finally, planar array antennas are available as fixed-beam microstrip arrays, slotted waveguide arrays, and beamforming arrays. Fixed array antennas cover frequencies up to 75 GHz while slotted waveguide arrays can reach 35 GHz. Additionally, a modular antenna system facilitates the construction of custom arrays for Multiple-Input Multiple-Output (MIMO) antenna systems that exploit multi-path propagation routes for increased channel capacity and improved system reliability. The modular array uses a practical realization to provide flexibility in forming the array size. The basic building block, i.e. the radiation element, is a single patch antenna that offers 6 dBi nominal gain with beam widths of and 50 degrees in the Vertical or E Plane and 95 degrees in the Horizontal or H Plane. A technical paper provides design details, antenna performance, and the mechanical structure for various MIMO antenna configurations [6]. Representative models of array antennas are shown in Figures 13A, 13B and 13C. A 4x16 MIMO array is illustrated in Figure 13D.

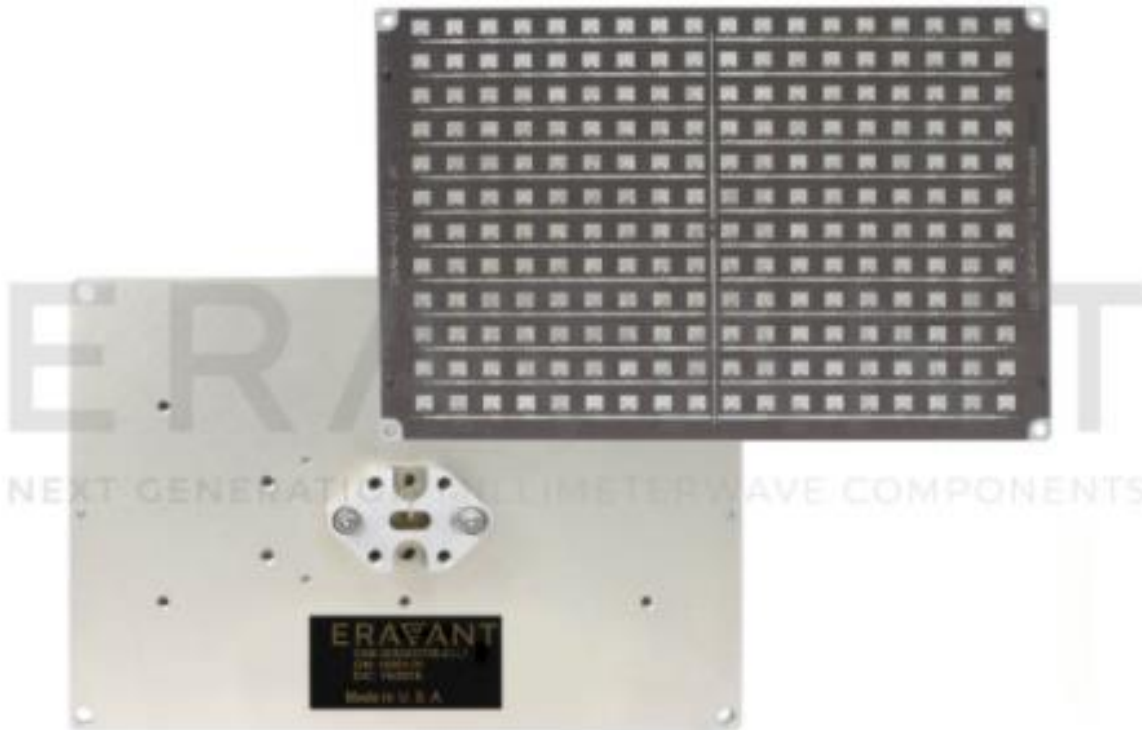

Figure 13A. A fixed beam microstrip antenna array operates at 24.125 GHz

Figure 13B. A 35-GHz slotted waveguide array antenna offers 27 dBi Gain

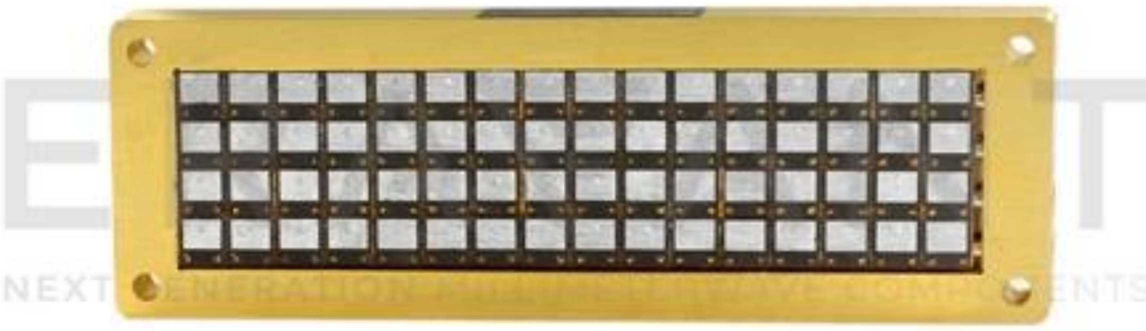

Figure 13C. Model SAM-2832830695-DM-L1-64C is a 28-GHz 64-elements array antenna

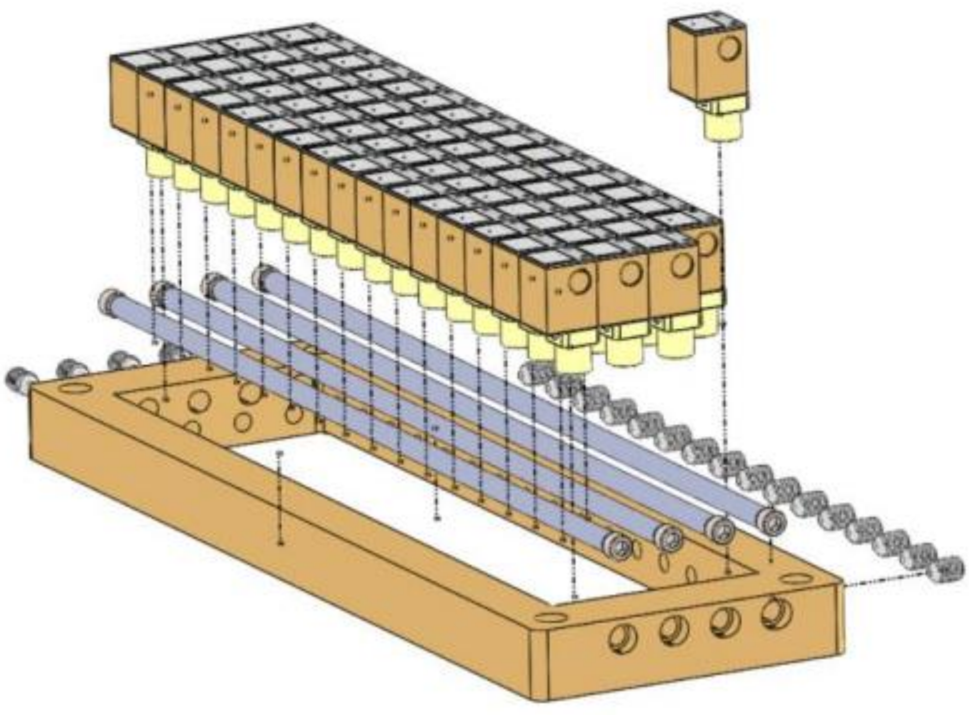

Figure 13D. Assembly illustration for a 4x16 modular phased array antenna

Passive and Interconnection Components

Modern microwave and mm-wave subsystems are configured based on two major transmission line formats, rectangular waveguides and coaxial cables. The waveguide is still the dominant transmission line in the mm-wave bands, while coaxial cables are catching up to reach 110 GHz using 1 mm connectors. Waveguide remains dominant because of its low loss characteristics and higher power handling capacity. Coaxial cable offers mechanical flexibility and lower weight where electrical performance is a less of a concern.

Passive and interconnection components are important elements in mm-wave subsystem design and construction. These components appear in both waveguide and coaxial configurations to include power dividers, directional couplers, magic tees, filters, diplexers, terminations, adapters, and various waveguide components such as bends, twists and straights. As a result, transitions between the two major transmission media are usually unavoidable. Therefore a wide range of waveguide-to-coax adapters is offered to cover the frequency range of 7 to 125 GHz in 13 waveguide bands, WR-112 to WR-08. Coaxial ports range from Type N to 1 mm connectors. Figures 14A and 14B illustrate WR-10 to 1 mm adapters in end-launch and right-angle configurations. Other components such as power dividers, filters, directional couplers, waveguide terminations, and flexible waveguides are shown in Figures 14C, 14D, 14E, 14F, and 14G. Many other adapters covering complete waveguide bands and their coaxial connector counterparts are offered as COTS products.

Figure 14A, SWC-101F-R1, WR-10 to 1 mm Adapter, End-Launch

Figure 14B, SWC-101F-R1, WR-10 to 1 mm Adapter, Right-Angle

Figure 14C. SWP-75311408-10-E2-H, 8 Way Power Divider for 75 to 105 GHz

Figure 14D. SWF-96312460-12-L1 Lowpass Filter, 60 to 96 GHz

Figure 14E. SWD-1040H-10-DB W-Band dual directional coupler covers 75 to 110 GHz

Figure 14F. SWL-1057-S8, W-Band 500-Watt High Power Load

Figure 14G. SWG-22118-FB-FT-A-G, WR-22 300-mm flexible waveguide section

Millimeter-wave Packaging

Component packing has been a constant challenge to the mm-wave industry. Despite recent advancements in surface-mount packaging technologies [8], connectorized components that contain bare semiconductor die are still playing a major role when electrical performance is the priority. In addition, the final RF interfaces of any microwave or mm-wave system are either coaxial or waveguide, driven by common antenna port configurations. Therefore the waveguide interface is still the preferred and most common solution for packages to achieve the best system performance.

Coaxial connector types, SMA through 1.85 mm, are widely used in the mm-wave industry to cover frequencies up to 67 GHz with reasonably good RF performance. Recent progress has pushed operating frequencies beyond 110 GHz with 1 mm and 0.8 mm connectors. Coaxial connectors offer easy packing adaptations and minimize engineering efforts when glass bead feedthroughs are used. Currently, the highest frequency glass bead available is for 1.85 mm connectors. Therefore, special feedthrough designs are required for packages utilizing 1 mm connectors. In contrast, waveguide-interfaced packages often require completely new engineering designs, as well as a custom designed package that is costly and time consuming to produce.

Following the concept of the coaxial connector, waveguide connectors were developed. The novel devices were recently invented and trademarked as Uni-Guide™ connectors. They are used in exactly the same way as flange-mount two-hole coaxial connectors. Figures 15A, 15B and 15C illustrate their assembly details.

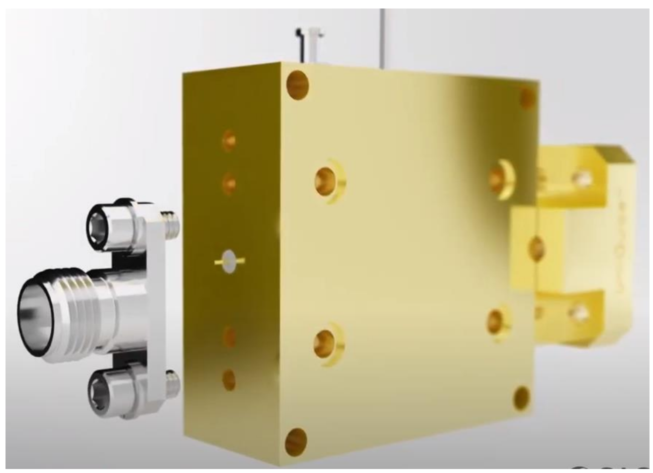

Figure 15A. A coaxial connector interfaces to a glass-bead feedthrough

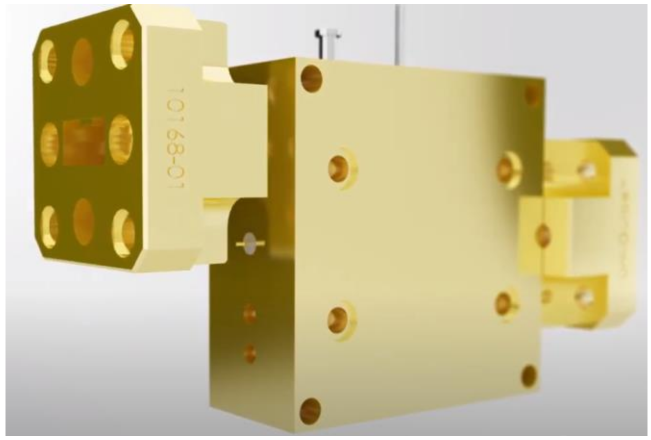

Figure 15B. A waveguide connector interfaces to a glass-bead feedthrough

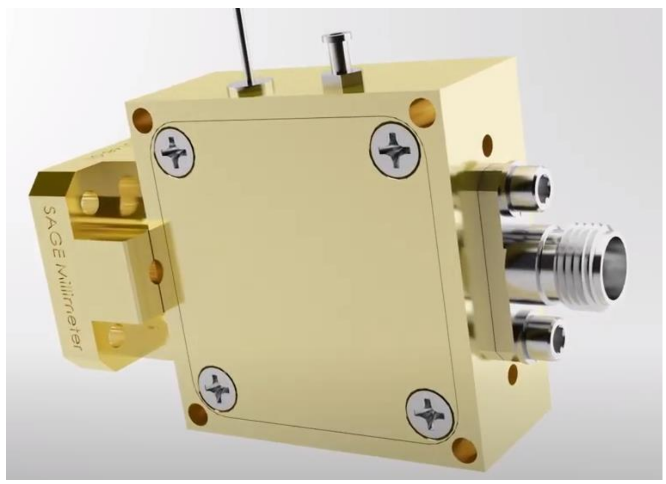

Figure 15C. A waveguide connector is used the same way as a coaxial connector

The performance of the waveguide connectors is similar to that of their coaxial counterparts. Figure 16 shows measured results for a WR-28 waveguide connector.

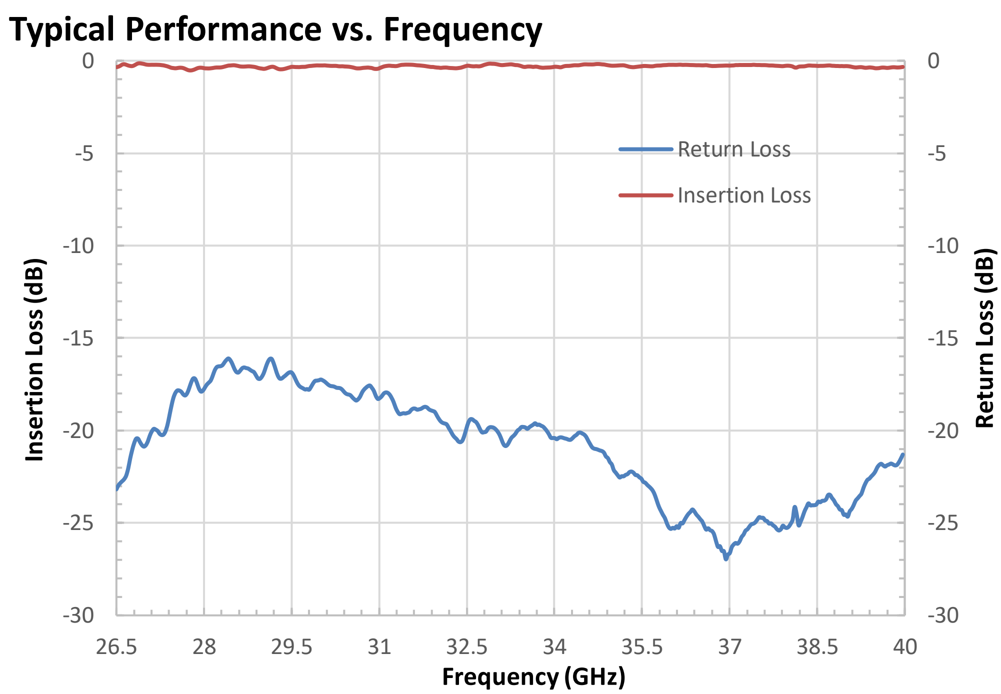

Figure 16. Measured Performance of Model SUF-2812-480-S1

Currently, standard waveguide connectors cover the WR-28, WR-22 and WR-19 waveguide bands. Figure 17 shows the product family. These connectors have mounting holes that accept 2-56 screws with 0.48-inch separation between the screws, to match a common industry format for coaxial connectors. For other bands, such as WR-42, WR-15 and WR-12, coaxial package designs must be modified to accept the waveguide connectors. This is because the standard 0.48-inch screw separation for coaxial connectors is not compatible with the waveguide or flange dimensions.

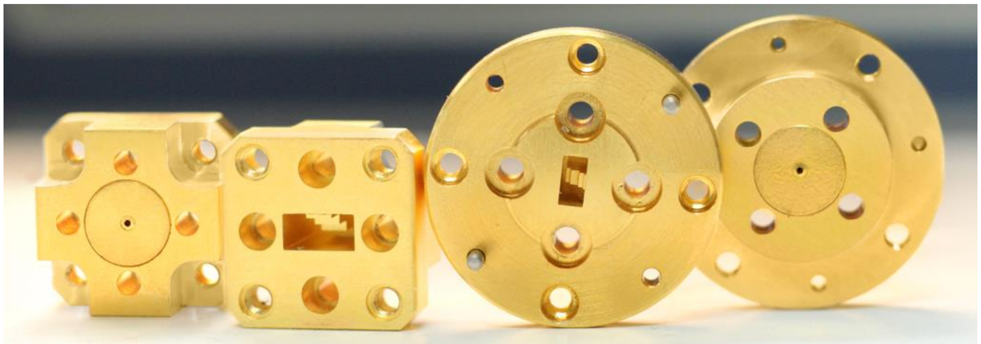

Figure 17. A Photo of Ka, Q and U Band Uni-Guide

The benefits that component manufacturers can now enjoy are,

1. Flexible package configurations including various connector types and waveguide orientations
2. Packaged devices with hermetic seals without expensive waveguide window technology
3. Waveguide interfaced packages without NRE costs and long development cycle times
4. Fewer standard packages for improved inventory efficiency

For system integrators, Uni-Guide™ connectors can also help to eliminate many interconnection devices, such as coax to waveguide adapters, waveguide twists and bends to make the system more compact and cost-effective. With all of these benefits, the Uni-Guide™ product family, from the device packaging and system integration points of view, not only helps to make mm-wave technology more accessible and affordable, but also reduces NRE costs and product development cycle times [12].

Millimeter-wave Testing

Another obstacle facing users of mm-wave technology is testing. Thanks to the maturity of the microwave industry's continuous development, the operating frequency of the most advanced microwave test equipment routinely covers 10 MHz to 50 GHz. Some options extend to 67 GHz and beyond. However, equipment operating higher than 67 GHz becomes much more expensive and less available. An alternative is to add frequency extenders to existing lower-frequency test equipment. A range of frequency extenders is available to extend microwave test equipment to 67 GHz and higher. This approach is typically used with microwave synthesizers, sweepers, spectrum analyzers, noise figure meters, and vector network analyzers (VNAs) to reach 50 GHz and above. Example frequency extender models are presented in Figures 18A, 18B, 18C and 18D. To support VNA testing, high-quality and cost-effective waveguide calibration kits are also offered for frequencies up to 220 GHz. A G-Band calibration kit is shown in Figure 19.

Common challenges facing mm-wave and THz measurement are,

1. Misalignment
2. Waveguide cocking
3. Screw insertion and adjustment
4. Waveguide bending and flange deformation
5. Time-consuming procedures

Figure 18A. An E-Band X4 frequency extender works with a 26.5 GHz synthesizer to generate signals from 60 to 90 GHz

Figure 18B. A W-Band harmonic mixer extends a 26.5-GHz spectrum analyzer to 110 GHz

Figure 18C. A D-Band Noise Figure and Gain test set operates up to 170 GHz

Figure 18D. A G-Band VNA extender works with a 20-GHz VNA to reach 220 GHz

Figure 19. A G-Band calibration kit covers 170 to 220 GHz

Among all microwave and mm-wave tests and measurements, 2-port network scattering parameters are the most demanding. To improve the quality, accessibility, and productivity of VNA testing, a number of innovative tools have been developed.

The waveguide Quick Connect tool improves the speed and accuracy of making temporary mm-wave waveguide connections. Two models work with common waveguide flanges used at frequencies from 33 GHz to 1 THz (Figures 20A and 20B). The benefits of the Quick Connect tools include:

1. Eliminates DUT surface scratching
2. Improves waveguide connection efficiency
3. Avoids waveguide cocking
4. Accommodates tight spacing between test equipment and DUTs
5. Forms secure waveguide connections during tests

Figure 20A. Quick Connect tools join waveguide flanges without using captive screws

Figure 20B. Quick Connect tools securely join waveguide flanges for rapid testing

Perhaps one of the most impactful mm-wave test system improvements is the recent development of a more effective contactless waveguide flange [8]. At Eravant, the Proxi-Guide™ contactless waveguide flange and the Wave-Glide™ rail positioning system were invented to greatly simplify and streamline the operation of VNA frequency extenders. The contactless flange is a waveguide section with a novel flange design that forms an RF choke when connected to another waveguide flange. The design eliminates the requirement for perfect mechanical contact between flanges. The rail positioning system allows repeatable positioning of mm-wave VNA frequency extenders. They perform easy alignment and rapid connections between the DUT and a test setup that employs contactless flanges. The contactless flange and the rail system are shown in Figures 21A and 21B, respectively.

Figure 21A. Contactless Flange

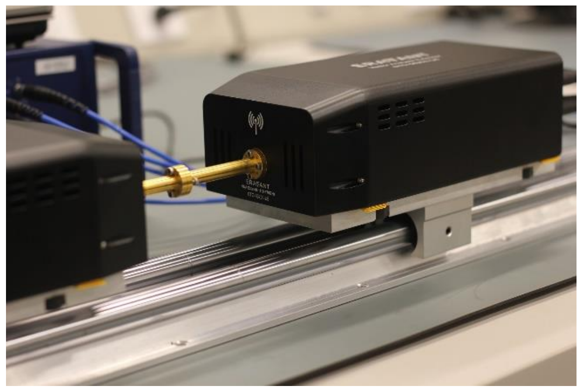

Figure 21B. Millimeterwave VNA Extender with Contactless Flange and Rail System

The Proxi-Flange™ contactless flange and Wave-Glide™ rail system offer the following benefits:

1. Allows more reliable and accurate test system calibration using an easy and rapid procedure
2. Eliminates calibration and testing errors caused by waveguide cocking to produce more accurate and reliable DUT test data
3. Helps hardware manufacturers deliver better quality DUT products without any wear on the flange threads or scratches on flange surfaces
4. Eliminates the need for highly skilled operators or technicians
5. Allows connections in tight spaces by eliminating screw insertion

6. Preserves test equipment accuracy and extends test equipment lifespan
7. Supports the testing of DUTs with non-standard flanges
8. Releases mechanical alignment stress, increases productivity, and guarantees consistent DUT test results
9. When used with computer-controlled actuators they can support fully automated high-volume production testing

Virtually all mm-wave test ports can be equipped with contactless flanges to realize faster and more reliable tests and measurement results. [14]

Conclusions:

Today, mm-wave COTS products offer total product solutions to engineers, researchers, and developers to construct and demonstrate future technologies and applications. Further, these products can also help to reduce the cost and cycle time of future system development and implementation. Novel waveguide connectors offer a new way to package waveguide-interfaced components and subsystems, As a result, many custom designed packages are avoided, saving development time and cost. A contactless flange and rail system, along with many frequency extender products, have the potential to greatly enhance mm-wave test and measurement systems. All this has made mm-wave technologies more accessible and more affordable for new applications.

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