Keysight Technologies
Measurement Considerations for Generating and Analyzing Millimeter-Wave Signals

Application Note
In applications that require high-speed, short-range connections, interest is growing in the use of signals that operate at millimeter-wave frequencies. Examples include satellite-to-satellite links, point-to-point radios, secure communications, and wireless audio and video connections.

Currently, the attraction of higher frequencies is less-crowded spectrum in the range of 30 to 300 GHz. The accompanying desire is wider modulation bandwidths that will enable greater data throughput.

Taken together, millimeter-wave frequencies and wider bandwidths lead to an increasing degree of difficulty in the measurement and characterization of signals and devices. Creating custom, in-house solutions is more challenging than it may seem because physical dimensions and tolerances shrink as frequency increases.

Fortunately, an increasing amount of commercial, off-the-shelf (COTS) equipment for millimeter-wave work is becoming available. For example, external COTS hardware can be used to extend the frequency range of proven microwave signal generators, signal analyzers and vector network analyzers. This saves time and effort, and helps ensure meaningful measurement results.

To provide a sense of what’s currently available, this application note provides a survey of the COTS millimeter-frequency signal generation and analysis tools currently available from Keysight Technologies, Inc. and two of our solution partners, OML, Inc. and Virginia Diode, Inc. (VDI). This note also includes pros, cons and suggested selection criteria that will help you choose the best solution for your requirements.
The challenges of working with millimeter frequencies

From 30 to 300 GHz, the associated wavelengths range from 10 to 1 mm. These extremely high frequencies have a number of attractive properties. For example, antenna dimensions can be very small compared to microwave antennas, and, as a result, transmitter and receiver systems can be very compact. In addition, the antennas can be highly directional with small beam widths. Currently, limited usage of millimeter spectrum means less crowding than in the VHF, UHF and microwave bands, and large modulation bandwidths are also available.

Turning a liability into an asset

With such short wavelengths, millimeter-wave signals exhibit interesting absorption properties that, at first, may seem problematic but can instead be turned into advantages. For example, in terrestrial applications these signals are rapidly absorbed as they propagate through the atmosphere. Absorption is especially high at the resonant frequencies of oxygen, water and carbon dioxide molecules.

Consequently, millimeter signals are most useful for short-range communications. Some of these rely on areas of low absorption: automotive radar (77 to 81 GHz), point-to-point radios, wireless backhaul links, and high-altitude radio-astronomy arrays. Others utilize areas of high absorption. For example, the Wi-Fi-compatible 802.11ad (WiGig) standard for high-speed audio and video links operates in the unregulated 60-GHz region. Unlike typical Wi-Fi signals, this frequency has a range of about 40 feet (about 12 meters) and is also attenuated by wood, stone and glass, making it a good choice for home-entertainment installations in apartment buildings, condominiums or townhomes. Coupling high-absorption properties with highly directional antennas enables creation of secure communication systems that minimize the chances of unauthorized eavesdropping.

Dealing with practical limitations

Developers of millimeter-based systems may encounter a number of difficulties. While losses through the atmosphere are high, they are even greater through transmission lines such as coaxial cable and waveguide.

As noted in the introduction, physical dimensions decrease as frequencies increase. Thus, all the associated hardware becomes smaller and more fragile, and manufacturing tolerances become much tighter. This also means it is much more difficult to fabricate and assemble millimeter-wave devices. Coupling these factors with today’s limited (but growing) demand for millimeter products translates into relatively high costs for components, assemblies and devices.

From a measurement perspective, it’s also worth noting the lack of traceable power standards above 110 GHz. Some end users have tried to address this by building power-measuring devices such as bolometers to ensure some level of measurement consistency and repeatability. However, supporting and maintaining these roll-your-own devices can also prove to be challenging.

1. Recently, research has been extending to frequencies up to 500 GHz or 1 THz, which is the sub-millimeter range.
Leveraging the growing availability of COTS equipment

Proven microwave signal generators, signal analyzers and vector network analyzers provide a foundation for viable measurement solutions at millimeter frequencies. With the Keysight PSG signal generator, external devices such as multipliers and upconverters can shift metrology-grade signals to higher frequencies. For signal analysis, harmonic mixers and downconverters translate millimeter-frequency signals downward into the range of high-performance instruments such as the Keysight PXA X-Series signal analyzer. Both types of external devices are necessary for successful vector network analysis at millimeter frequencies.

Keysight offers a variety of mixers, downconverters and upconverters that provide frequency translation for signal analysis up to 110 GHz (see sidebars on pages 10 and 13). The two solution partners mentioned earlier—OML and VDI—also provide a variety of COTS frequency extension devices.

OML supplies millimeter- and submillimeter-wave frequency extension products for vector network analyzers, scalar network analyzers, spectrum analyzers, converters and signal generators. Its solutions address the needs of R&D and manufacturing engineers in radio astronomy, communications, semiconductors, imaging, space research, biomedical and homeland security. For more information, please visit www.keysight.com/find/OML and www.omlinc.com.

VDI manufactures test and measurement equipment for millimeter-wave and terahertz applications. This includes modules that extend the performance of network analyzers, spectrum analyzers and signal generators to frequencies as high as 1.1 THz. VDI seeks to make the terahertz frequency band, spanning from 100 GHz through 3 THz, as useful for scientific, defense and commercial applications as the microwave and infrared bands are today. For more information, please visit www.keysight.com/find/VDI and www.vadiodes.com.

All of the approaches used by Keysight, OML and VDI—multiplication, upconversion, harmonic mixing and downconversion—have advantages and disadvantages. The subsequent sections of this note present a closer look at each technique in the context of either signal generation or signal analysis.
Exploring solutions in signal generation

Three essential topics will affect your choice of solution for signal generation: your application requirements, the pros and cons of the available generation methods, and the cost of the equipment. Naturally, the primary considerations are your application requirements. Four of these often stand out as crucial selection criteria: frequency range, output power, modulation and bandwidth characteristics, and spurious signals. All are directly related to the two most common generation methods—multiplication and upconversion.

Assessing generation via multiplication

The use of multipliers is a very popular solution. Configuration is relatively simple: you connect one or more multipliers to a microwave signal generator and shift the output frequency upward into the range of interest. For example, 6x multiplication of the output frequency can be accomplished by connecting the signal to a module that contains a doubler and a tripler working in series (Figure 1). If the signal generator output ranges from 12.5 to 18.4 GHz, the resulting multiplied signal will be in the W-band, covering 75 to 110 GHz.

Multiplier modules are easy to set up and use, typically requiring an external power supply and just one RF input cable connected to the output of the signal generator. To enhance this simplicity, the PSG is designed to work with millimeter source modules, providing the ability to enter the multiplication factor and then present the correct frequency on the instrument display.

The pros and cons of multiplier modules will help you decide if they are suitable for your application. On the plus side, this approach has four important attributes:

- Simple to set up and use, as noted earlier
- Works well with continuous-wave (CW) and pulse-modulated signals
- Designed for fixed output power; some modules offer a variable attenuator mounted at the output
- Readily available from commercial manufacturers

Figure 1. This simplified block diagram illustrates the inner workings of a 6x multiplier module. Most contain additional elements such as amplifiers, filters, isolation circuitry and input protection.
On the negative side, four factors arise with most multiplier modules:
- Operate with saturated output power
- Have issues with most types of modulated signals
  - Not suitable for most digitally modulated signals, especially those that involve
    amplitude changes (due to saturated output operation)
  - Degrade analog modulation (e.g., multiply the deviation of FM and $\phi M$ signals)
- Are inherently nonlinear
  - Severely distort AM (including QAM) due to saturated output operation
  - Create spurs at harmonic, sub-harmonic and non-harmonic frequencies
- May alter the rise and fall times of pulse-modulated signals (e.g., may be sharper
  than the original signal)
- Multiply the phase noise of the signal generator

This last problem can be quite prominent because the phase noise of the signal genera-
tor is multiplied up, rising by 6 dB with every doubling in frequency (i.e., by $20\log(n)$).
Figure 2 shows how the phase noise of a PSG signal generator increases when used with
a variety of OML source modules at frequencies up to 450 GHz.

![PSG phase noise vs. frequency due to 20log(n) multiplication (SxxMS-AG)](image)

Figure 2: The phase noise present on a 15-GHz output from a PSG signal generator visibly increases along with
the multiplication factor.
Assessing generation via simple upconversion

Compared to multiplication, the configuration for upconversion is more complex because even the simplest case requires a mixer and two signal generators, one providing the LO signal and the other producing the modulated IF signal (Figure 3). Some upconverting mixers include a built-in doubler in the LO path, making it possible to use a lower-frequency (and therefore lower-cost) signal generator as the LO source.

![Diagram showing upconversion](image)

**Modulation signal generator**

**LO signal generator**

Figure 3. With upconversion, high-side mixing ($F_{RF} = F_{LO} + F_{IF}$) produces the highest possible output frequency.

The pros and cons of upconversion will help you decide how well it fits your application.

On the plus side, this approach has four important attributes:
- Works well with modulated signals
- Can support wide-bandwidth signals
- Provides reasonable output power
- Better preserves the phase noise of the IF and LO signal generators

Unlike the multiplier approach, upconversion maintains a high degree of modulation fidelity, even with wideband signals. Depending on the conversion loss of the mixer, this configuration can provide enough output power for most applications.

On the down side, three factors affect the usefulness of upconversion:
- The configuration is more complex and potentially more expensive than with multiplication
- Mixing produces an image signal at twice the IF frequency and below the desired signal
- Mixing produces spurious signals at harmonic, sub-harmonic and non-harmonic frequencies

As another possible negative, amplitude control is very limited. A modest amount of amplitude control can be achieved at the mixer output by varying the strength of the LO and IF signals. However, pushing the power too high can overload the mixer, potentially causing not just distortion but also physical damage to the mixer. When greater control is needed, a variable attenuator can be connected to the RF output.
One last point: Although a large number of upconverting mixers are available, it can be difficult to find a model with the required combination of LO, IF and RF frequencies along with a low enough conversion loss to deliver the required output power.

Enhancing upconversion with dedicated devices

The next level of integration beyond a simple mixer is a dedicated upconverter. For example, the Keysight N5152A is a custom upconverter designed to produce WiGig (802.11ad) signals in the 57 to 66 GHz range. As shown in Figure 4, the rear panel has inputs for the LO and IF signals as well as a frequency reference and DC power; the front panel has a V-band waveguide output flange and control knobs for manually operated attenuator settings.

The N5152A takes an LO signal between 10 and 12 GHz and mixes it with a 5 GHz IF signal. To minimize conversion loss, the LO signal is multiplied by 4 and then filtered to help prevent sub-harmonics and other spurious signals from reaching the mixer.

As shown in Figure 5, the 5-GHz IF input signal goes through a first stage of upconversion to an IF frequency of 17.5 GHz and then is filtered before final upconversion to the desired frequency band. Because only the upper sideband is needed, a high-pass filter is used to block the lower sideband and a variety of undesired mixing products. Finally, the upper sideband passes through an output amplifier and one or more attenuators to provide power control at the RF output.
Because the WiGig standard defines a very wideband OFDM signal (e.g., 2 GHz wide), careful selection of individual components is essential to ensuring that the upconverter maintains adequate bandwidth and a reasonably flat frequency response throughout the signal path. This helps maintain signal fidelity to a level that ensures a WiGig receiver can accurately demodulate the signal.

Exploring solutions in signal analysis

When you need to characterize millimeter-wave signals or transmitters, two essential topics come into play: the application requirements and your analysis needs. The four most important requirements are frequency range (often a standard waveguide band), sensitivity (affected by conversion loss), the modulation and bandwidth characteristics of the signal-under-test, and the likelihood of spurious signals from either the environment or the test setup. Individually and collectively, these factors affect the best choice of external hardware for your application: harmonic mixer, smart mixer or downconverter.

Extending spectrum analysis with harmonic mixing

The use of an external harmonic mixer is a classic technique that has been around for decades. A suitable spectrum or signal analyzer has ports that provide access to the LO and IF signal paths inside the instrument.

As shown in Figure 6, the LO signal is routed to the external unit, which contains a diode-based mixer. This generates harmonics of the LO, and these mix with the incoming RF signal at the mixer’s waveguide port. Such mixers are typically optimized to produce an excellent IF response at a specific harmonic number. This IF signal is routed back into the spectrum analyzer for processing in the same way it would handle an IF signal generated by its built-in microwave mixer.
The diagram in Figure 7 shows how the external mixer fits into the block diagram of the spectrum analyzer. Unlike the internal microwave mixer, there is no attenuation or filtering (i.e., preselection) ahead of the mixer. As a result, it is necessary to be cautious about overloading the mixer with a too-powerful signal that may produce distortion or, worst case, cause physical damage to the mixer. Fortunately, most harmonic mixers use waveguide input ports, and waveguide is very good at rejecting signals below its cutoff frequency and thereby shielding the mixer from the effects of lower-frequency signals.

Figure 7. The insertion of an external harmonic mixer into the signal path of a 50-GHz PSA signal analyzer can extend its measurement range to 325 GHz.
The pluses and minuses of this approach will help you decide if it can satisfy your application requirements. Three attributes exist on the plus side:
- The test setup is relatively simple, as shown in Figure 6
- The waveguide input port rejects signals below the cutoff frequency
- Individual mixers are optimized for a specific harmonic within a waveguide band

In contrast, five negatives must be considered:
- Each waveguide band requires a separate harmonic mixer
- Conversion loss increases as frequency increases
- Signal-to-noise ratio (SNR) decreases as frequency increases
  - Causes a higher displayed average noise level (DANL)
  - Results in reduced sensitivity
- There is no built-in attenuation or filtering
  - Large signals can overload a harmonic mixer
  - Large signals can cause distortion as well as physical damage
- Harmonic mixing creates both correct and image responses

This latter point can have a significant impact on the quality of your measurement results. For example, the mixing process produces a correct response at the LO frequency minus the IF and an image response at the LO frequency plus the IF. Mixing also creates additional signals that are the product of the input signal and other harmonics.

### Table 1. Each 11970-Series mixer addresses a specific waveguide band.

<table>
<thead>
<tr>
<th>Model</th>
<th>Frequency range (GHz)</th>
<th>LO harmonic number</th>
<th>Maximum conversion loss (dB)</th>
<th>Nominal spectrum analyzer noise (dBm, 1 kHz BW)</th>
<th>Frequency response (dB)</th>
<th>Nominal gain compression (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11970K</td>
<td>18 to 26.5</td>
<td>–6</td>
<td>24</td>
<td>–105</td>
<td>±1.9</td>
<td>–3</td>
</tr>
<tr>
<td>11970A</td>
<td>26.5 to 40</td>
<td>–8</td>
<td>26</td>
<td>–102</td>
<td>±1.9</td>
<td>–5</td>
</tr>
<tr>
<td>11970Q</td>
<td>33 to 50</td>
<td>–10</td>
<td>28</td>
<td>–101</td>
<td>±1.9</td>
<td>–7</td>
</tr>
<tr>
<td>11970U</td>
<td>40 to 60</td>
<td>–10</td>
<td>28</td>
<td>–101</td>
<td>±1.9</td>
<td>–7</td>
</tr>
<tr>
<td>11970V</td>
<td>50 to 75</td>
<td>–14</td>
<td>40</td>
<td>–92</td>
<td>±2.1</td>
<td>–3</td>
</tr>
<tr>
<td>11970W</td>
<td>75 to 110</td>
<td>–18</td>
<td>46</td>
<td>–85</td>
<td>±3.0</td>
<td>–1</td>
</tr>
</tbody>
</table>

### Using harmonic mixers with X-Series signal analyzers

Keysight X-Series signal analyzers equipped with the external-mixing option (Option EXM) are designed to simplify the use of external harmonic mixers. For example, instead of using separate cables for the LO and IF signals, a built-in diplexer routes the two signals onto a common coaxial cable.

Compatible mixers also have a single LO/IF connector that mates with the single cable. Some of these require a DC bias to ensure minimum conversion loss. Option EXM includes a built-in bias source that provides the necessary DC voltage through the same coaxial cable. The net result is a cleaner and simpler test setup than that used with the PSA.

### Harmonic mixers from Keysight

Designed for use with PSA spectrum analyzers, the Keysight 11970-Series unpreselected harmonic mixers employ a dual-diode design to achieve flat frequency response and low conversion loss. Table 1 summarizes the key attributes of the six 11970 models, each of which has a harmonic number that addresses a specific waveguide band. As you can see, the higher the frequency band the greater the conversion loss in the mixer. One consequence: the reduction in SNR results in a higher DANL and reduced sensitivity.
As a further enhancement, Option EXM includes “image shift” and “image suppress” functions that compensate for the lack of preselection in the external mixer. These remove the image pair produced by the mixing equation, FRF = n*(FLO±FIF), where n is the specific harmonic number of the mixer. In addition to the image pair, the input signal mixing with other harmonics creates additional unwanted responses. The image-shift function bumps up the LO by twice the IF frequency, causing all the false responses to move in frequency while the real responses remain stationary on the screen. The companion image-suppress function removes the false responses from the display.

**Enhancing signal analysis with smart mixers**

Keysight’s “smart mixers” provide further improvements in the performance and functionality of external mixing when used with X-Series signal analyzers. Four models are available, covering three bands—V, E and W—and extending frequency range up to 110 GHz. All support modulation bandwidths up to 300 MHz.

The mixers include onboard electronics that provide a more integrated solution, and the addition of a USB connection enables communication between mixer and analyzer. Through the USB link, the mixer can identify itself and provide information such as harmonic number, LO path-loss data and conversion-loss calibration data. As described in the preceding section, the diplexer built into the signal analyzer enables the use of just one coax cable for the LO and IF signals.

LO signal level is one of the variables that can affect the performance of external mixers. For example, it can be difficult to accurately predict the LO signal level at the mixer because it depends on the length and quality of the cable that carries the LO signal from the analyzer. Keysight smart mixers use a built-in detector to measure the LO signal level across the entire frequency range then build up a correction table. The mixer then adjusts its gain to compensate for up to 10 dB of cable loss (Figure 8).

![Smart Mixer block diagram](image)

Figure 8. The electronics inside an Keysight smart mixer ensure improved performance by boosting the LO signal to compensate for cable loss.
With these capabilities, the smart mixers have more advantages than disadvantages.

The pluses:
- Simple test setup
- Numerous automatic functions that ensure accurate results
  - Identification of mixer model and serial number
  - Setting of default frequency range and LO harmonic numbers
  - LO alignment at startup
  - Recalibration when time and temperature change
  - Amplitude correction and transfer of conversion-loss calibration data
  - LO amplitude adjustments to compensate for path loss
  - Excellent conversion loss of 27 dB maximum, which improves DANL and TOI
  - Excellent amplitude accuracy

The three drawbacks may be relevant to your situation or application:
- Work only with X-Series signal analyzers
- Maximum frequency is limited to 110 GHz
- Degrades phase noise performance

This last point is similar to what occurs in signal generation (refer back to Figure 2). In signal analysis with harmonic mixing, the same $20 \log(n)$ relationship applies and phase noise increases at higher frequencies (Figure 9). In this example, a 525-GHz signal has phase noise of $-74 \text{ dBc/Hz}$ at a 10-kHz offset from the carrier. To determine if the phase noise is actual or limited by the combined mixer/analyzer performance, it is necessary to compare measured results to the performance specifications of the instruments.

![Figure 9. The X-Series phase noise measurement application computes values at specific offsets, providing a starting point for evaluation of the performance of the mixer/analyzer combination.](image-url)
Smart mixers from Keysight

Designed for use with X-Series signal analyzers, the Keysight M1970-Series waveguide harmonic mixers extend measurements up to 110 GHz. The “smart mixer” capabilities, USB interface, and single-cable connection shorten overall start-up operations and ensure better performance. Table 2 summarizes the key attributes of the four M1970 models, each of which has a harmonic number that addresses a specific waveguide band. Figure 10 illustrates the improvement in DANL compared to traditional mixer designs.

Table 2. Each M1970-Series mixer addresses a specific waveguide band.

<table>
<thead>
<tr>
<th>Model</th>
<th>Frequency range (GHz)</th>
<th>LO harmonic number</th>
<th>Maximum conversion loss (dB)</th>
<th>Nominal noise figure (dBm)</th>
<th>Nominal gain compression (dB)</th>
<th>Nominal system DANL (dBm; 1 Hz RBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1970E</td>
<td>60 to 90</td>
<td>–6 / –8</td>
<td>27</td>
<td>40</td>
<td>–1</td>
<td>–136</td>
</tr>
<tr>
<td>M1970V, Opt. 001</td>
<td>50 to 75</td>
<td>–6</td>
<td>23</td>
<td>36</td>
<td>–1</td>
<td>–140</td>
</tr>
<tr>
<td>M1970W</td>
<td>75 to 110</td>
<td>–8</td>
<td>25</td>
<td>38</td>
<td>–1</td>
<td>–138</td>
</tr>
</tbody>
</table>

Figure 10. Compared to traditional mixers, the inherent performance of the smart mixer combined with correction techniques results in significantly better conversion loss and therefore improved DANL.
Improving signal analysis with downconversion

Millimeter-range downconverters are the third way to improve measurement performance. Depending on the design of the signal analyzer and the downconverter, the configuration requires two or three pieces of equipment: the signal analyzer and downconverter, and perhaps a signal generator to provide a higher-frequency LO signal.

With most downconverters, the LO signal—whether provided by the signal analyzer or a signal generator—is multiplied and amplified before entering the mixer. Depending on the downconverter design, the mixer may perform either fundamental mixing or operate on a low-order harmonic. The latter approach results in lower conversion loss, thereby improving DANL.

Some of the available downconverters are designed for specific applications. For example, the Keysight N1999A WiGig downconverter is optimized for just the 801.11ad frequency band (57 to 66 GHz); however, it offers the 2-GHz bandwidth required by WiGig signals.

The N1999A is an example of a downconverter that uses an external signal generator to provide a higher-frequency LO (Figure 11). This signal is multiplied by 4 before entering a mixer that operates in fundamental mixing mode. The 5-GHz IF signal is routed to the signal analyzer’s RF input port. This high IF frequency is necessary to enable the wide 2-GHz bandwidth of the WiGig signal.

Figure 11. The N1999A WiGig downconverter uses a signal generator to provide an LO signal that enables greater bandwidth than is possible using the IF input port of a signal analyzer or oscilloscope.
Analyzing digitally modulated signals

In general, a signal analyzer using the techniques presented here—harmonic mixing, smart mixing and downconversion—can easily characterize continuous-wave (CW) signals as well as those that carry analog or pulse modulation. In contrast, digitally modulated signals require the use of more powerful analysis tools.

This is the forte of the Keysight 89600 VSA software, which is a comprehensive set of tools for demodulation and vector signal analysis (VSA). These tools enable you to explore virtually every facet of millimeter-wave signals that have been downconverted into the range of a signal analyzer or oscilloscope (Figure 12). The software can run inside an X-Series analyzer, in an Infiniium oscilloscope or on an external PC connected to the instrument via LAN.

Figure 12. Through digital demodulation, the 89600 VSA software enables detailed analysis of a 64QAM signal: constellation diagram (upper left), error vectors versus time (upper right), frequency spectrum (lower left) and parameters for such as error vector magnitude (EVM; lower right).
Conclusion

Access to innovative measurement solutions is essential to early research into next-generation wireless technologies and systems. For those working at millimeter-wave frequencies, an increasing amount of COTS equipment is becoming available from Keysight and our solution partners. This saves time and effort while ensuring that you achieve meaningful measurement results.

As shown here, no single technique is necessarily superior to the alternative approaches that can be used for signal generation and signal analysis. The key to success is assessing the advantages and disadvantages of each technique as they relate to your measurement requirements, in-hand equipment and available budget.

Related information: Keysight

- Millimeter-wave signal generation: www.keysight.com/find/SG_mmwave
- Millimeter-wave signal analysis: www.keysight.com/find/SA_mmwave
- PSG signal generator: www.keysight.com/find/PSG
- PSA signal analyzer: www.keysight.com/find/PSA
- 11970-Series harmonic mixers: www.keysight.com/find/11970series
- PXA X-Series signal analyzer: www.keysight.com/find/PXA
- EXA X-Series signal analyzer: www.keysight.com/find/EXA
- 89600 VSA software: www.keysight.com/find/89600

Related information: OML

- Solution brief: Millimeter-Wave Signal Generators, Keysight publication 5990-9814EN
- Solution brief: Millimeter-Wave Spectrum Analysis, Keysight publication 5990-9813EN
- Online: www.keysight.com/find/OML and www.omlinc.com

Related information: VDI

- Technical overview: Millimeter-Wave Frequency Extenders from Virginia Diodes, Inc. for the Keysight PSG Signal Generators, Keysight publication 5991-3162EN
- Technical overview: Millimeter-Wave Frequency Extenders from Virginia Diodes, Inc. for the Keysight X-Series Signal Analyzers, Keysight publication 5991-3161EN
- Online: www.keysight.com/find/VDI and www.vadiodes.com