Application Note

Harmonic Mixer Primer: The Gateway to the Millimeter Wave Frontier is Harmonic Mixer Technology

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The next frequency frontier is the millimeter wave (mm-wave) band, which occupies the 30 GHz to 300 GHz spectrum (wavelengths from 10 to 1 mm). Emerging applications now span radio astronomy, communication, imaging, space research, and homeland security, and are starting to seriously populate this vast spectrum resourse. Market forecast and limited available spectrum suggest that attractive growth is just over the horizon so explorers are naturally migrating to stake their claim in this next frontier.

Those intrepid explorers of this mm-wave frontier need reliable and economical tools to investigate, design, characterize, model, test, troubleshoot, maintain, and verify key performance attributes of their applications. Unfortunately, convenient off-the-shelf mm-wave tools are very limited commercially. Practically speaking, most engineers improvise by extending their existing test equipment into this mm-wave spectrum with frequency extension accessories based on harmonic mixer technology.[1] The purpose of this article is to overview the low-cost harmonic mixer technology (retail pricing is currently between $2,000 and $6,000 USD) and to present practical tips on how to apply this commercially available down conversion technology to spectrum analysis as a means to explore the mm-wave frontier.

Harmonic Mixer Primer

Overcoming frequency limitations in available instrumentation involves using frequency extension accessories based on harmonic mixer technology to down convert the mm-wave spectrum into the signal analyzer's bandwidth for analysis. In a typical external mixer setup, the harmonic mixer bridges the gap between the mm-wave output from the DUT and the lower frequency spectrum analyzer input (see **Figure 1**). In this way, the harmonic mixer provides the enabling technology for mm-wave measurements.

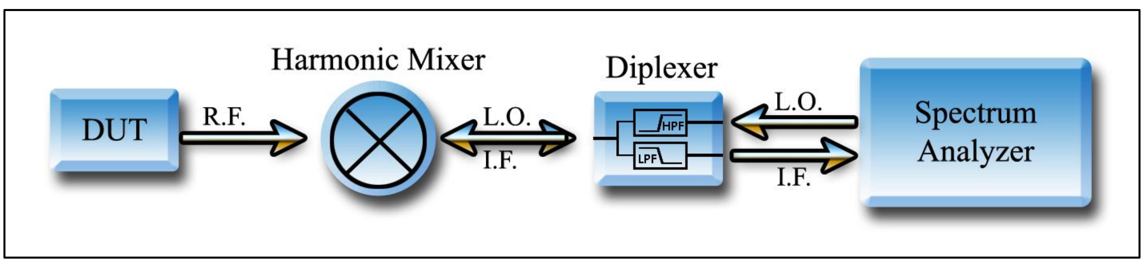


Figure 1. *This harmonic mixer setup converts DUT mm-wave band (R.F.) to a predefined I.F. frequency that the spectrum analyzer can process. This setup functionally relies on an external mixer option in the spectrum analyzer for the necessary L.O. and I.F. interconnects to the harmonic mixer and automatically displays the desired signal parameters. Once connected, the nth harmonic of the L.O. frequency mixes with the mm-wave frequency (R.F.) to produce the predefined I.F. frequency. Conversion loss of the harmonic mixer is proportional to the multiplier factor, n. This popular setup depends on a diplexer for signal separation, which can be either external or internal to the spectrum analyzer.*

With an external mixer option, the harmonic mixer operation with the spectrum analyzer is transparent to the user. The harmonic mixer with waveguide interface can conveniently connect to the mm-wave output of the DUT or to a waveguide antenna. On the opposite side of the harmonic mixer, a reasonable length coaxial cable (e.g., 1 meter) offers efficient access to the spectrum analyzer, including the diplexer. After selecting the corresponding waveguide band on the spectrum analyzer, the engineer can use their familiar instrument to conduct mm-wave measurements on their DUT. For accurate amplitude measurements, additional offset features are available in the spectrum analyzer to manually compensate for the conversion loss of the harmonic mixer. In this way, this frequency extension accessory offers an attractive value proposition to engineers with mm-wave requirements.

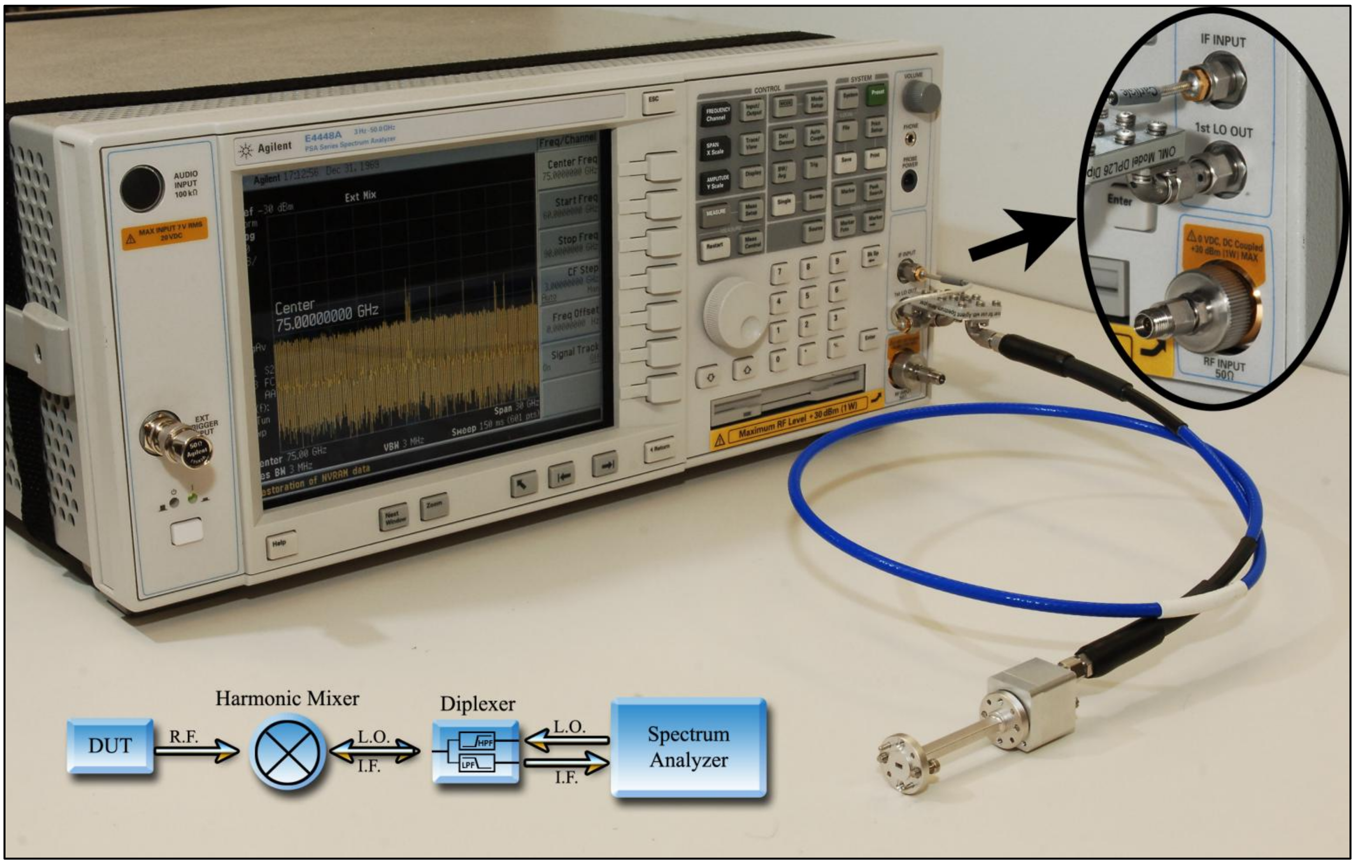


Figure 2. *A typical mm-wave measurement setup includes the microwave spectrum analyzer, in this case an Agilent PSA Model E4448A, the OML M12HWD WR-12 harmonic mixer, and the OML DPL-26 diplexer. Cabling is efficient and unobtrusive. The inlay shows close-up interconnects between the diplexer and the IF and LO inputs provided with the external mixer option.*

As background, the spectrum analyzer's external mixer option enables substitution of the harmonic mixer for its own R.F. front-end design to overcome the mm-wave measurement limitation. After substitution, the later stages in the spectrum analyzer's receiver chain are still utilized for the remaining signal analysis capabilities. Harmonic mixer suppliers use spectrum analyzer manufacturer's designated L.O., I.F., and multiplier factor to characterize their harmonic mixers (with bias, if available).[2] The correction process is easy to implement using the supplier's final test data.

Once connected, the harmonic mixer design down converts the R.F. signal by mixing the nth harmonic of the L.O. to generate the predefined I.F. of the existing instrument. The R.F. input and the harmonics from the L.O. drive mix to produce I.F. that satisfies the equation of n(L.O.) – (R.F.). As an example, the Agilent PSA (E444xA) high performance spectrum analyzer with predefined I.F. of 321.4 MHz has multiplier values that can range from n=14 for WR-15 to n=48 for WR-03 (see **Figure 3**). Typically, firmware automatically handles the multiplier factor so the displayed start and stop frequencies are the desired mm-wave R.F. spectrum. In addition, offset compensation is possible so displayed amplitude corrects the conversion loss of the harmonic mixer. In a typical measurement scenario, the display readout offers actual results with real-time updates when using the harmonic mixer technology with the spectrum analyzer.

Rectangular Waveguides

Below 50 GHz, commercially available instrumentation using coaxial connections are available for convenient and affordable signal analysis, as well as reasonable cable losses. In order for the engineer to overcome the 50 GHz threshold will require new skills with waveguide as a tool, which excels at the low-loss transmission of mm-wave frequencies. In particular, these explorers also need to equip themselves with the popular waveguide band segmentation, flanges, and dimensions (see **Figure 3**). With this information, the engineer can translate their application into the proper frequency extension accessory that is based on these same industry standard waveguide terminologies.

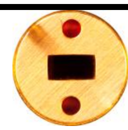
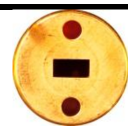
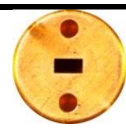
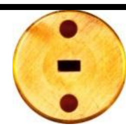
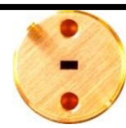
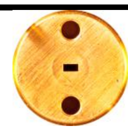
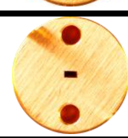
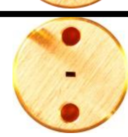
Waveguide Spectrum	TE_{10} Cutoff Frequency (GHz)	Rectangular Waveguide Interface View	Internal Dimensions (mils)	Agilent PSA Multiplier Factor, n
50 – 75 GHz **WR-15** V-Band	39.9 GHz		148.0 x 74.0	14
60 – 90 GHz **WR-12** E-Band	48.4 GHz		122.0 x 61.0	16
75 – 110 GHz **WR-10** W-Band	59 GHz		100.0 x 50.0	18
90 – 140 GHz **WR-08** F-Band	73.8 GHz		80.0 x 40.0	22
110 – 170 GHz **WR-06** D-Band	90.8 GHz		65.0 x 32.5	26
140 – 220 GHz **WR-05** G-Band	115.7 GHz		51.0 x 25.5	32
170 – 260 GHz **WR-04** Y-Band	137.2 GHz		43.0 x 21.5	38
220 – 325 GHz **WR-03** H (J)-Band	173.6 GHz		34.0 x 17.0	48

Figure 3. *This overview shows the popular 50 to 325 GHz mm-wave spectrum by waveguide band. This breakdown table also contains the key rectangular waveguide information for TE_{10} propagation mode, including the aperture size both dimensionally and visually for relative comparisons. The cutoff frequency indicates the frequency above which electromagnetic energy will propagate in the corresponding waveguide. Dimensions are proportional to the wavelengths, which decrease with higher frequencies. The multiplier factor (n) is a harmonic mixer value chosen by the analyzer manufacturer that down converts the millimeter to the microwave spectrum for easier analysis in modern spectrum analyzers.*

Measurement Example

For most convenient readouts, modern spectrum analyzer features can compensate for the external harmonic mixer attributes so amplitude and frequency readouts are accurate. For amplitude readouts, the harmonic mixer manufacturer supplies the typical amplitude correction factor (i.e., conversion loss) value, which is largely influenced by the nth harmonic of the L.O. signal needed to down convert the R.F. to the predefined I.F. for signal analysis. As one might expect, the conversion loss increases with higher multiplier values (see **Figure 4**). For simplified frequency readouts, the spectrum analyzer contains preset settings, selectable by waveguide band, to compensate for the multiplication factor so the frequency scale reads R.F. instead of L.O. or I.F.

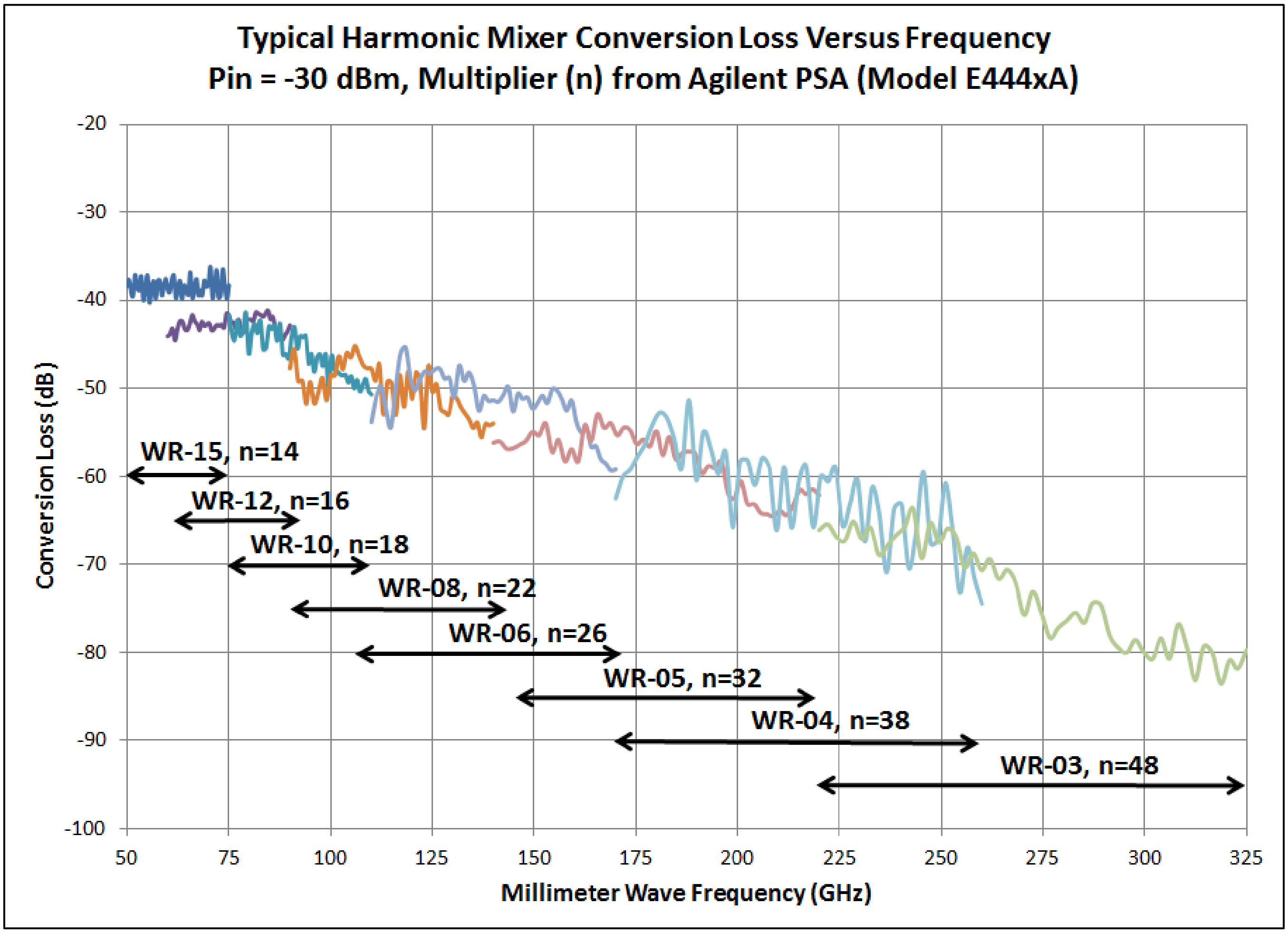


Figure 4. *This chart presents representative conversion loss of a single diode unbalanced harmonic mixer versus the mm-wave frequency range for the Agilent PSA Signal Analyzer (model E444xA). As predicted, the multiplier factors are overlaid with the typical conversion loss values to show how conversion loss increases with the multiplier value. These results are typical for the predefined L.O. and I.F. capabilities of the PSA. Results may vary when using other spectrum analyzers due to different settings for L.O., I.F., and multiplier factors.*

Independently verifying operation of the harmonic mixer requires a mm-wave source with a known power level. Simply set the R.F. source to a value in the harmonic mixer's linear range (i.e., avoid input compression with approximately – 30 dBm). Using **Figure 1**, apply this "reference" R.F. signal to the input of the harmonic mixer and complete the L.O. and I.F. connections to the spectrum analyzer (an external diplexer may be necessary). After properly configuring the spectrum analyzer for external mixer operation, the readout will display a measured value that includes the reference signal level and the harmonic mixer's conversion loss. By entering the conversion loss as an offset, the spectrum analyzer will display the known power level. This approach verifies the setup is working properly.

Figure 5 shows an example screen capture from the Agilent PSA (model E444xA). As with all spectrum analyzer-based measurements, engineers can optimize frequency span, RBW, and VBW settings for preferences in accuracy and display updates. As an advanced tip for better results, built-in image suppression and image identification features in the spectrum analyzer can simplify interpretation of measurement results by eliminating unwanted mixing products.[3] Refer to the spectrum analyzer's operating manual for more details.

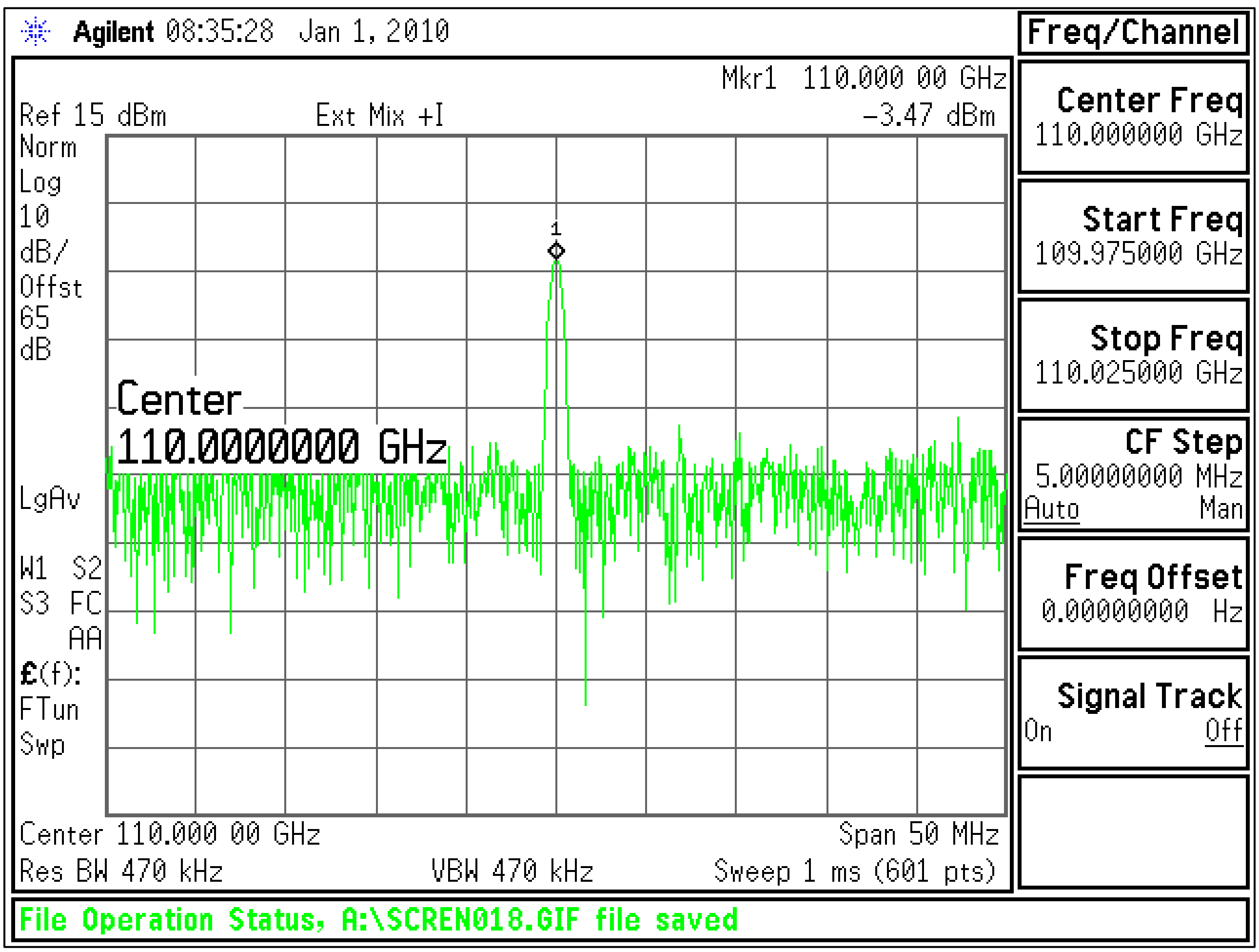


Figure 5. *This is a mm-wave measurement screen capture from the Agilent PSA Signal Analyzer (model E4448A). To compensate for the harmonic mixer conversion loss, a correction factor (or offset) is applied to the amplitude for readout convenience. Note that the frequency scale also shows compensation for the multiplication factor. The external mixer option in the spectrum analyzer helps make the harmonic mixer look transparent in the measurement setup.*

Measurement Considerations

Damage Level. The maximum input power is typically +20 dBm where nominally +15 dBm is allocated to the L.O. signal. Maintaining composite power levels below +20 dBm ensures damage will not occur to the harmonic mixer diode(s).

Linearity. Mixers are inherently non-linear devices so careful selection of power levels will help optimize the results. Position measurements in the linear input range, which practically speaking means to avoid applying input signals within 10 dB of the 1 dB compression point. Below -30 dBm input power, single diode unbalanced harmonic mixers typically provide both accurate and repeatable measurements when using high performance spectrum analyzers.

Mixer Topology. Balanced mixers are popular for their increased linearity performance; however, they also fundamentally limit harmonic mixing to only even products due to the balanced properties in this topology. This may be a good selection as long as the spectrum analyzer utilizes even harmonic multipliers in their external mixer option. In contrast, the single diode mixer offers more versatility to use both even and odd products with less L.O. power, which are the reasons for their popularity in mm-wave applications. The single diode topology also requires bias, which can be useful to "peak" responses and further optimize results.

Image Rejection. There will be numerous mathematical intersections occurring where these harmonic currents, m + n, combine to produce responses within the spectrum analyzer's I.F. bandwidth. Furthermore, the strongest of these I.F. responses can in turn be combined with other m + n products to produce additional I.F. responses. Do not be alarmed that the results on a spectral display look like a "picket fence." Instead, most high performance spectrum analyzers offer "image rejection" features to eliminate "false" from the "desired" results; thereby, simplifying the signal analysis task.

Conversion Loss & Dynamic Range. Frequency extension using harmonic mixer technology is a valuable tool for measuring fundamental characteristics of mm-wave signals, but not without some trade-offs. As a general observation, the higher conversion loss versus higher frequency behavior reduces measurement dynamic range and might be an obstacle when measuring low-level signals (i.e., intermodulation distortion products, discrete spurious, or noise figure). As a tip, it's important to analyze after external mixing (taking into account the conversion loss) whether sufficient dynamic range (i.e. signal-to-noise ratio) exists in the spectrum analyzer for accurate measurements. Generally speaking, accurate measurements require greater than 10 dB signal-to-noise ratio.

Diplexer Characteristics. The diplexer is essential to the successful operation of the harmonic mixer, especially in single diode harmonic mixers. Although it is more convenient when the diplexer is integrated into the spectrum analyzer, this is not always the case. For example, the Agilent PSA (model E488xA) requires an external diplexer as part of their external mixer setup. In this case, the predefined I.F. is 321.4 MHz and the available L.O. range is 2.9 GHz to 7.0 GHz. The diplexer design will ensure these frequencies will flow unimpeded and with adequate signal separation to optimize performance for mm-wave spectrum analysis (see **Figure 6**). The diplexer characteristics are occasionally worthwhile to consider in the setup since they constitute hardware constraints.

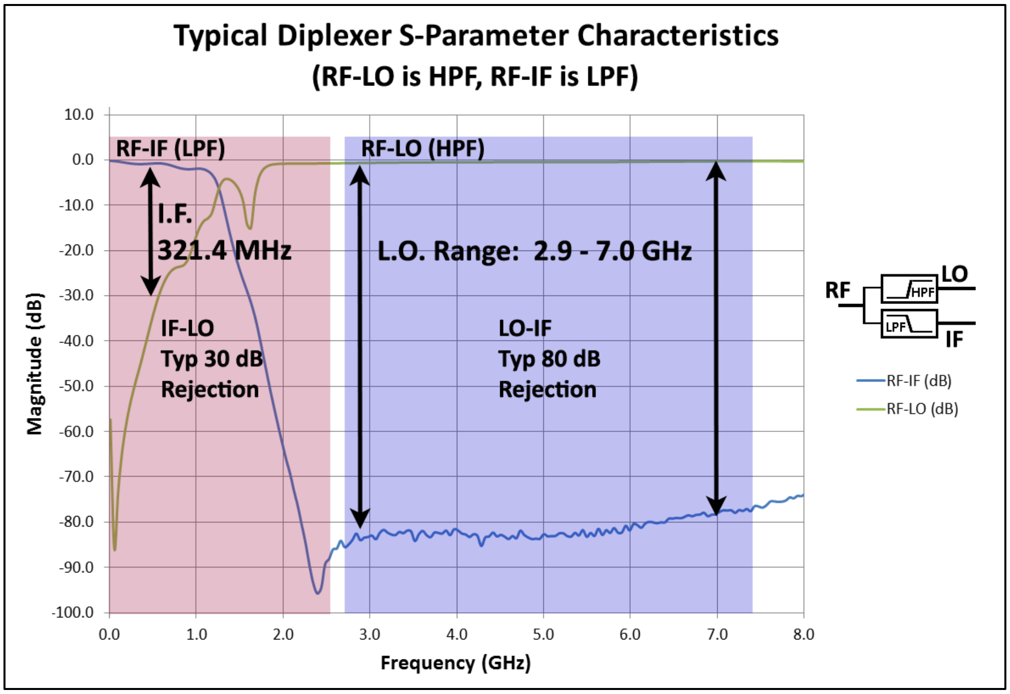


Figure 6. *The diplexer's design for external mixing is optimized for signal separation and harmonic mixing performance at the predefined I.F. and available L.O. range of the spectrum analyzer. The Agilent PSA (model E444xA) utilizes a predefined I.F. of 321.4 MHz and has an available L.O. range of 2.9 GHz to 7.0 GHz. This typical S-parameter overlay capture shows the RF-IF and RF-LO paths which provide low insertion loss and filtering to satisfy these requirements.*

Summary & Conclusion

The harmonic mixer technology enables the practical measurement of millimeter wave signals. This primer overviewed harmonic mixer technology, including the typical conversion loss versus the millimeter waveguide bands for single diode harmonic mixers. This primer and tips will ensure that engineers can explore the mm-wave frontier using the terminologies and frequency extension accessories as practical tools. This technology is also the foundation for additional frequency extension accessories deployed in mm-wave signal generation, scalar, and vector network analysis.

References

1. M. Sayed, "Millimeter Wave Tests and Instrumentation," 65th ARFTG Conference Digest, June, 2005, pp. 28-37.
2. OML, Inc. Application Note, "Using a Millimeter Wave Harmonic Mixer to Extend the Frequency Coverage of a Spectrum Analyzer," 42-010124, January, 2001.
3. Agilent Technologies Application Note #1485, "External Waveguide Mixing and Millimeter Wave Measurements with Agilent PSA Spectrum Analyzers," 5988-9414EN, October, 2007.

About OML, Inc.

OML, Inc., located in the Silicon Valley of California, is a premier supplier of innovative millimeter wave frequency extension products for VNAs, scalars, spectrum analyzers, and signal generators. For more information, please visit our website at www.omlinc.com.