Application Note

Using a Millimeter Wave Harmonic Mixer to Extend the Frequency Coverage of a Spectrum Analyzer

Until recently, harmonic mixers have been used in every microwave spectrum analyzer produced. It is only with the advent of spectrum analyzers such as the Tektronix 2782, that wideband fundamental mixing has been used. Harmonic mixing has been and remains the most widely used method of covering frequencies above 40 GHz. A few vendors have manufactured fixed L.O. frequency, block down converters to extend spectrum analyzer coverage. OML has produced one version of a block down converter covering 22 to 40 GHz for one test equipment OEM, and another down converter covering 18 to 40 GHz for a second test equipment OEM.

Keysight (Agilent/ HP) and Tektronix (Tek) have been the major sources of harmonic mixers for millimeter wave spectrum analysis. The HP 3 port harmonic mixers have been difficult to use with analyzers other than HP, restricting their widespread use. The Tektronix 2 port harmonic mixers have been relatively easy to use with spectrum analyzers built by vendors other than HP and Tek and, and have generally been cited as the unit of choice by those vendors.

Governmental Mandates

This paper is an attempt to provide an overview of the measurement criteria that must be considered when using millimeter wave harmonic mixers in spectrum analysis. Recent changes in FCC rules regarding the measurement of harmonic and spurious content through the fifth harmonic for certified devices has put new pressures on millimeter wave spectrum analysis. Under the FCC CFR47 Part 15 (RF Devices) standard[1], products that do not require an operator’s license shall meet specific radiated emissions for spurious and harmonics in the frequency bands between 40 and 200 GHz. These rules were apparently approved in the absence of power calibration standards above 95 GHz. Similar requirements are occurring worldwide. In addition to the governmental actions, the number of new millimeter wave applications is surging. OML has since received hundreds of calls from various organizations seeking ways to make the necessary measurements.

These new industry needs and a general lack of understanding of the proper techniques involved in the millimeter wave measurements requires that the engineer examine all historical references available on the subject of millimetric measurements. It may be that some new technical treatise will be required to adequately explore the measurement requirements induced by these governmental and industrial expansions.

Current State of Measurement Technology

Historically, the engineer has used an HP or Tek harmonic mixer with some degree of confidence for making millimeter wave measurements. The engineer would use the mixer deemed appropriate by the spectrum analyzer manufacturer. Relatively new design analyzers contained an approximate amplitude (dB) “offset” to provide “correct” amplitude information for each of the spectrum analyzer/harmonic mixer combinations. An exacting engineer would then consult the manufacturers uncertainty specifications to determine the error boundaries of his measurements. These “error boundaries” were developed to take into account the typical variance in individual mixer and spectrum analyzer performance. The mixer conversion loss and input return loss were the major variables for the mixers. The variability in L.O. power provided and I.F. sensitivity were the contributors for the spectrum analyzers.

When the engineer uses an older HP spectrum analyzer with the HP 3 port mixer, he has to add the conversion loss shown on the side of the mixer to the amplitude read from the analyzer. In the case of the earlier HP 2 port mixers and the Tek 2 port mixer the conversion loss was not specifically provided, however limited data could be found in the manufacturer’s catalog or analyzers user’s manual. Again, the error boundaries would have to be applied. Using the conversion loss shown on the side of the mixer is somewhat problematical as the user is forced to assume that the mixers performance can be interpreted as a linear function between the data points shown. That assumption can be as faulty as is the case above, where the spectrum analyzer manufacturer assumes flat conversion loss for their amplitude “offset”. In both cases the mixer data depends on a limited number of data points which are generally taken at equal frequency intervals across the band. The accuracy of any interpolation between the data is an engineering judgment call.

As mentioned earlier, other vendors have configured their spectrum analyzers for the use of external millimeter wave harmonic mixers. Examples of the newer and more popular models are cited below. *Consult your Operators Manual* in detail before investing in or using harmonic mixers. Most of the spectrum analyzer manufacturers (other than HP) had engineered their products with the Tektronix millimeter wave harmonic mixers in mind. Be careful, the previous observations, concerning the variance of the available L.O. power and the I.F. sensitivity, apply double. Spectrum analyzer manufacturers have typically not paid much attention to the effects of L.O. power on millimeter wave spectrum analysis when designing their L.O. output function. Some vendors do not provide enough power to adequately pump a harmonic mixer and most vendors have L.O. power variance of up to 5 dB across the band. Use of the adjustable built-in DC bias provided by most manufacturers will help mitigate problems such as insufficient or excessive L.O. power to some extent on a discrete frequency basis.

It is impossible to properly calibrate the full band performance of a millimeter wave harmonic mixer under these conditions. The engineer should map the available L.O. power across the output frequency range. This information can be then used to analyze the potential performance of a harmonic mixer vs. its L.O. specification and adjustments made to the performance expectations. The engineer always wants to use the highest L.O. frequency range possible for the lowest harmonic number if there is a choice. Most of the analyzers listed below will have some assumed amplitude correction built in for their readout function. This built-in amplitude correction may or may not be reasonably correct. The engineer must confirm the performance of this function as discussed earlier.

Manufacturer	Series	I.F. MHz	L.O. GHz	Adjust. Bias	Freq. Readout & Harmonic (1)	Built-in Diplexer
Advantest	R3271A	421.4	3.42-7.92	Yes	Yes/Fixed	Yes
	R3272	421.4	3.42-7.92	Yes	Yes/Fixed	Yes
	R3273	421.4	3.42-7.92	Yes	Yes/Fixed	Yes
Anritsu	MS2830A	1875	5.0-10.0	Yes	Yes/Fixed	Yes
	710	521.4	3.0-6.0	Yes	Yes/Fixed	No
	2802	521.4	3.0-6.0	Yes	Yes/Fixed	Yes
	2667C	689.3	3.5-7.0	Yes	Yes/Fixed/User	Yes
	2668C	689.3	3.5-7.0	Yes	Yes/Fixed/User	Yes
Keysight (Agilent/ HP) (2)	N9030A	322.5	3.8-14.0	Yes	Yes/Fixed/User	Yes
	E444xA	321.4	2.9-7.0	Yes	Yes/Fixed/User	No
	70000	321.4	3.0-6.6	Yes (No)	Yes/Fixed/User	No
	8566	321.4	2.3-6.8	Yes	Yes/Fixed/User	No
	856x (Late)	310.7	3.0-6.8	Yes	Yes/Fixed/User	No
	E440x	310.7	3.0-6.8	Yes	Yes/Fixed/User	No
IFR(Marconi)	930/ 940	410.7	3.0-12.0	No	Yes/User	No
	1800	410.7	3.0-12+	No	Yes/User	No
	2393	410.7	3.0-12.0	No	Yes/User	No
R & S	FSV	729.9	7.7-15.3 (3)	Yes	Yes/Fixed/User	Yes
	FSEK/M	741.4	7.5-15.2 (3)	Yes	Yes/Fixed/User	Yes
	FSIQ	741.4	7.5-15.2 (3)	Yes	Yes/Fixed/User	Yes
	FSM/ESMI	221.4	5.2-13.1 (4)	Yes	Yes Fixed	Yes
Tektronix	49x/ 27xx	2000	2.0-6.0	Yes	Yes/Fixed	No (5)
	2782/ 84	525/3525	8.1-17.9	Yes	Yes/Fixed/User	Yes
W & G	SNA-33	421.99	3.5-7.9	No	? / ? / ?	No

Notes:
(1) Some models allow the user to set or change the harmonic number, consult the Operator's Manual.
(2a) HP 8566A/B requires the #11975A L.O. amplifier for proper operation of the HP 11970x series mixers. Do not use this amplifier with single-diode harmonic mixers as its bias voltage is not applied through its I.F. port to the harmonic mixer (as is more commonly done with the majority of spectrum analyzers).
(2b) HP 70000 has three different input modules that can interface with external mixers. All three should have the harmonic mixer I.F. signal connected to the module's I.F. input through a 1 dB attenuator to provide a DC return path for the mixer's self-generated bias. These input modules are: the HP 70909A and 70910A which do not have bias available, and the HP 70907A/B which does have bias available but in a manner not easily used with harmonic mixers.
(3) Option FSE-B21 can be used to enhance external mixer operation.
(4) Requires an external L.O. amplifier Model # FS-Z30 for external mixer operation.
(5) Tek P/N 015-0385-00 diplexer is required for external mixer operation.
(6) For other Manufacturers and Models: consult the Spectrum Analyzer's Operations Manual.

Balanced versus Unbalanced Harmonic Mixers

Any user who has used harmonic mixers has experienced frustration of “identifying” or determining that the displayed signal is the “real” desired signal. The false images that appear on the spectrum analyzer screen are created by the many unwanted mixing products produced by the harmonic mixing action. The unbalanced, single diode harmonic mixer produces unsuppressed I.F. responses equal to m(R.F.) + n(L.O.) for both positive and negative products. That is, for every imaginable multiple of the R.F.(m) and of the L.O.(n) there will be a mixing products produced. As the spectrum analyzer sweeps the L.O. frequency provided to the mixer, the L.O. (n) energy causes harmonic currents to be generated in the mixer diode. Likewise, the R.F. (m) energy under analysis also causes harmonic currents to be generated in the diode. 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. The results are a spectral display that looks like a field of weeds from which the user must select that one stalk of wheat. After the desired signal has been “identified” the user must adjust the mixer bias, provided by the spectrum analyzer, for optimum signal response.

The balanced, two diode harmonic mixer has advantages and disadvantages as compared to the unbalanced harmonic mixer. A significant advantage is that the balancing action of the mixer will tend to suppress unwanted L.O. harmonic mixing products. For example, odd L.O. harmonic mixing products are suppressed in an even harmonic mixer. Even L.O. harmonic mixing products are suppressed in the odd harmonic mixer. The degree of suppression depends on the “balance” of the mixer and is typically about -20 dBc. Other higher order mixing products also tend to be suppressed because of lower unwanted I.F. energy levels. The spectral result of all this suppression is a much “cleaner” display from which to identify the desired signal. The balanced nature of the diodes also eliminates the need for bias.

Elimination of the bias requirement simplifies the use of the harmonic mixer, however, the use of two diodes increases the L.O. power required. The increased L.O. energy requirement and the inability to use both even and odd harmonic mixing prevents effective usage of the balanced harmonic mixer with many of the spectrum analyzers currently available on existing test benches. Spectrum analyzers listed in the previous chart above, showing only a fixed harmonic number, fall into this category.

Proper Measurement Calibration and Error Boundaries

The procedure that should be used to make quality millimeter wave spectrum analysis measurements is to calibrate the spectrum analyzer/harmonic mixer combination, at the frequency of interest, with a signal of known amplitude. This should be accomplished at the desired signal frequency and can only be relied upon over a very narrow bandwidth about that frequency. The harmonics of the signal of interest will probably fall into higher frequency waveguide bands, necessitating use of a different harmonic mixer. Proper analysis of each of these harmonics will, in turn, require that each setup be calibrated with a known signal level at the harmonic frequency of interest. Now the assortment of equipment required has grown. The user must have a signal source for each frequency to be investigated and a power measurement system to identify the correct amplitude of that signal. It quickly becomes apparent why the typical engineer chooses to rely on the data supplied with the harmonic mixer.

At this point the engineer should consider the operational condition of his spectrum analyzer. Is the L.O. output power supplied by the analyzer for use with the harmonic mixer, within specification? Is the sensitivity of the spectrum analyzers “external IF”. input, used with the harmonic mixer, meeting specification? These two test conditions are usually assumed by the engineer and during most equipment calibrations they are not even addressed. The lack of proper calibration of these two specifications is even more pronounced with older spectrum analyzers. Improper L.O. level, both high and low, can have a very negative impact on harmonic mixer conversion loss. This problem will cause degradation in the operation of a balanced, multi-diode harmonic mixer and will more severely affect an unbalanced single diode mixer. Inattention to these test specifications can distort the measurement data, often to the disadvantage of the engineer. The sad part is that in the majority of acceptance testing, the engineer has neglected to apply the error boundaries to the test results.

The Penalties of Short Cuts

Additional problems arise if the harmonic mixer is not used properly. It is common to see a millimeter harmonic mixer used outside of its band. The reason given is that “it is not very far out of band and the mixer seems to work fine”. This reasoning is especially prevalent above 110 GHz where most organizations do not have a mixer for each band. The engineer must remember that he is using a **“harmonic”** mixer and that they, by their very nature, generate harmonics. Customers have actually complained that their Q Band mixer was not functioning properly when they were testing a 38 GHz radio. The engineer was measuring a 38 GHz signal and then trying to measure the second harmonic at 76 GHz with the same mixer. First problem is that the engineer was assuming flat conversion loss.

As stated above, that is most likely not the case "in band" and most assuredly not the case "out of band". Then came his statement "that the second harmonic response was huge". What was happening is that the harmonic mixer was generating the second harmonic which it was then down converting to the spectrum analyzer. The engineer must take this harmonic generation into account when choosing which waveguide band mixer to use. The proper mixer to be used for measurement of a harmonic is the one that will cover that harmonic's frequency within mixer's designed frequency band and whose cutoff frequency will reject the fundamental signal and harmonics below that being analyzed. The engineer should also remember to buffer the signal source with an isolator or attenuator as the full source power will be reflected by the cutoff waveguide.

Unfortunately, this improper out-of-band usage was inadvertently encouraged by the way Tektronix had split up the millimeter wave bands in their spectrum analyzers. The Tek 494AP spectrum analyzer has the following band splits: 18-27 GHz, 26-40 GHz, 33-60 GHz, 50-90 GHz, 75-140 GHz, 110-220 GHz and 170-325 GHz. Tektronix never claimed that their harmonic mixers could be used over those broad frequency ranges, their catalog very specifically limited the mixers bandwidth to the proper waveguide frequency bands. As so often happens, the user will take short cuts without the proper research and analysis being applied. Another typical example is that a company will buy the minimum number of mixers required to cover a total frequency range, i.e. WR-42, WR-28, WR-19, WR-12 and WR-10 to cover 18 to 110 GHz. This sounds fiscally prudent but ignores not only the question of the mixers out-of-band performance or lack thereof, but it also fails to make use of the very desirable waveguide cutoff phenomena. The fiscally prudent decision also fails to take into account the cost of the waveguide transitions needed to allow rigorous measurement of the in-between bands not covered by the limited selection of mixers chosen.

A list of the waveguide frequency bands and their cutoff frequencies is shown below to aid in further understanding the problems illustrated above.

W/G Band	Freq. GHz	Cutoff GHz	W/G Band	Freq. GHz	Cutoff GHz
WR-42	18-26.5	14.08	WR-10	75-110	59.05
WR-28	26.5-40	21.07	WR-08	90-140	73.84
WR-22	33-50	26.34	WR-06	110-170	90.84
WR-19	40-60	31.41	WR-05	140-220	115.75
WR-15	50-75	39.86	WR-04	170-260	137.52
WR-12	60-90	48.35	WR-03	220-325	173.28

How can the calibration signal be accurately measured?

The availability of new millimeter wave power sensors is somewhat limited and no one manufacturer offers a complete line. Millitech offers the thermistor mount type of waveguide power sensor that operates with the HP 432 series power meters. Originally developed by the Hughes millimeter wave organization, the sensitivity range of these sensors is -20 to +10 dBm. Millitech has listed in their catalog full band sensors covering WR-28 through WR-10 and limited band coverage of WR-08 and WR-06. The prudent engineer will insist on testing "used" Millitech or Hughes thermistor sensors before buying as they are quite fragile and are easily damaged by excessive power. HP offers coaxial power sensors covering up to 50 GHz and waveguide power sensors for WR-28, WR-22 and WR-10. These sensors and the older HP thermistor mount waveguide sensors for WR-42 and WR-28 are available on the "used" market.

Anritsu has manufactured the full range of millimeter waveguide power sensors in the past, but latest reports indicate that they are now limited to WR-42 through WR-12. WR-42 through WR-10 Anritsu sensors may be available on the "used" equipment market. There are very few WR-08 power sensors available on the "used" test equipment companies. These WR-08 sensors have been found to be usable to 220 GHz and beyond when used with the appropriate waveguide transitions. The cutoff frequency of the selected transition now supplies the desired cutoff function. There are some older WR-06 and WR-05 Anritsu waveguide power sensors, in the hands of a few scientific institutions, and they are considered priceless. The Anritsu sensors are generally felt to be the most desirable as they are the most robust, exhibiting the best stability and have the widest sensitivity range, -20 to +20 dBm. The Anritsu sensors are most often used with the Anritsu ML-83A power meter (they can be used with the ML-4803A with adapters). They can also be used with a newly developed Anritsu power meter with adapters. Anritsu has coaxial power sensors, for use with the new power meter, that cover up to 65 GHz. Boonton manufactures a power meter with optional waveguide diode based sensors up through 100 GHz. Millitech manufactures the sensors for the Boonton meter and they both sell the complete system. Dorado sells an imported calorimeter that can be used up to 325 GHz when equipped with the proper waveguide transitions. Their usefulness for millimeter wave harmonic mixer calibration is limited by their lack of sensitivity. The lowest signal level measurable is -10 dBm (maximum is +30 dBm) and harmonic mixers typically start to compress at -20 dBm especially above 100 GHz.

Calibration services for millimeter power sensors are relatively easy to find for WR-42 and WR-28 and are less available for WR-22. Calibration services of sensors covering WR-19 through WR-10 are harder to find with Hughes and TRW in California being two of the better known sources. The engineer will want to demand traceability to N.I.S.T. N.I.S.T. currently has standards with continuous coverage up through 75 GHz and WR-10 coverage of 93 to 97 GHz per their Web site. OML has not been able to find any other reputable organization throughout the world that has recognized calibration standards above 97 GHz at this time. A late note, the British National Physics Lab (NPL) are current proving out what they call a "Photo-acoustic power standard" with power measurement capability from 60 to 300 GHz.

This system is supposed to be difficult to use, requiring an extremely stable environment, and a long measurement time for each measurement.

Above 97 GHz, all meaningful power sensor calibration is referenced to a calorimeter. Calorimeters have been commercially manufactured in the WR-42 or WR-28 waveguide bands and must be used with waveguide transitions to cover the higher bands. To be sufficiently accurate, a calorimeter must be calibrated with an N.I.S.T. traceable precision DC power source and voltage/current meter. The return loss and power to heat conversion efficiency of the calorimeter must be known accurately. The insertion loss of any waveguide transition must also be accurately characterized. The measurement of the calorimeter return loss and the waveguide transition insertion loss can be accomplished with a vector network analyzer (VNA) equipped with a suitable millimeter wave frequency extension package. When using a VNA to measure these parameters, the reference standards for the measurements are waveguide devices whose **physical properties** have been precisely determined. Most scalar analysis systems are not recommended at these frequencies because of the inability of the scalar detectors to distinguish between the desired signal and other spurious and harmonics that may emanate from the signal source. The scalar detectors are often able to detect signals quite removed from the waveguide band of interest. When a scalar system is used it must have either a fundamental or well filtered source (spurious and harmonics <-50 dBc) to medicate the out-of-band response of the detector. There is currently no governmental or commercial service available for the characterization of the calorimeter power to heat conversion efficiency above 97 GHz, so the user must depend on the calorimeter manufacturer's data which are somewhat open to question. The current method of arriving at agreement about the accuracy of a power measurement above 97 GHz is to compare the measurement result of one organization to that of other organizations, a process called "mapping".

It would appear to the prudent engineer that there is no possible method available to make accurate spurious and harmonic suppression measurements above 97 GHz to the satisfaction of any future FCC requirements.

If an engineer can achieve a measurable calibration signal at the frequency of interest, the signal must then be attenuated to a level of less than -20 dBm to avoid harmonic mixer compression during calibration. Fixed value waveguide attenuators are not wide band and exhibit a pronounced attenuation slope, low to high in attenuation increasing in frequency, and must be calibrated at the frequency of use. A terminated directional coupler can be used as a good wide band attenuator, but must also be calibrated prior to use. Typical good directional coupler flatness will be less than 2 dB across the band of interest. The best attenuator to be used would be a precision rotary vane attenuator. These attenuators are full band and very flat by nature. A Hughes designed rotary vane attenuator is available from Millitech from WR-28 through WR-06. "Used" Hughes and Alpha rotary vane attenuators are available with the Hughes being considered to be the most accurate. These attenuators can be most accurately calibrated with a millimeter wave capable vector network analyzer.

Notes

1) A white paper authored by Tom Cokenias (reference OML pn 42-000218), a well-known engineering consultant in the area of FCC certification, exploring the various FCC rules and regulations requiring harmonic and spurious testing up through 200 GHz.

2) In response to numerous inquiries regarding flange compatibility issues received by OML, the following compatibility information has been developed.

Waveguide	Waveguide Frequency (GHz)	Current Designation	Mil-f-3922/ Number	Flange Configuration	Historical Flange (UG)
WR-42	18 –26.5	K	68-001KM	0.875” sq.	595/U
WR-28	26.5 – 40	Ka	68-001AM	0.750” sq.	599/u
WR-22	33 – 50	Q	67B-006	1.125” rd.	383/U
WR-19	40 – 60	U	67B-007	1.125” rd.	383/U-M
WR-15	50 –75	V	67B-008	0.750” rd.	385/U
WR-12	60 –90	E	67B-009	0.750” rd.	387/U
WR-10	75 –110	W	67B-010	0.750” rd.	387/U-M (10)
WR-08	90 –-140	F	67B-08	0.750” rd.	387/U-M (08)
WR-06	110- –170	D	67B-06	0.750” rd.	387/U-M (06)
WR-05	140 –220	G	67B-05	0.750” rd.	387/U-M (05)
WR-04	170 –260	Y	67B-04	0.750” rd.	387/U-M (04)
WR-03	220 –325	H (J)	67B-03	0.750” rd.	387/U-M (03)

This paper is being treated as a living document and will continue to be updated with new information as is developed. The reader is encouraged to respond to OML with any suggestions, clarifications or criticism.