Harmonic Mixers for VNA extenders to 900GHz

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Abstract— **Harmonic mixers for high frequencies have been available for many years but conversion loss has always been relatively high and usually with many dips in the frequency response. There are many devices covering the lower waveguide bands, but relatively little above 110GHz. As part of Rohde & Schwarz's new line of VNA extenders, Radiometer Physics (RPG) has designed a new range of waveguide harmonic mixers, covering from 24.5 to 900GHz with excellent performance. Part of this work includes complete redesign and fabrication of extremely low parasitic anti-parallel mixer diodes by two independent, competing groups: RAL and ACST. These diodes can also be used to make excellent sub-harmonic mixers (2nd harmonic of the LO) with high sensitivity. We also outline the use of a wideband stripline filter, using a "photonic band gap" structure and an unconventional waveguide transition for the RF signal coupling.**

I. Introduction

Recent years have seen an increasing interest in extremely high (sub-mm) frequencies by the microwave industry. The technology to reach these high frequencies has only recently moved from the exotic to main-stream. Use of sub-mm instrumentation includes high-resolution security scanners [1], quality control of thin materials [1], atmospheric ice-cloud studies by satellite [2] or high-altitude balloon or aircraft [3], and ultra secure high-speed data links. Test equipment for these sub-millimetre wavelengths (>300GHz) has previously been limited to over-moded versions of lower frequency devices, with poor performance. Radiometer Physics has developed a new range of high-performance, broadband, balanced mixers and frequency sources, which are used to make test equipment to enable sub-millimetre engineers to use the same methods as millimetre or microwave engineers. These individual devices will be discussed, as well as the test equipment that can be built from them. Several other groups (Oleson OML, Virginia Diodes) are developing similar test equipment for this rapidly expanding field and interest in sub-mm wavelengths is certain to increase.

II. Harmonic Mixers

A key to using spectrum analysers and Vector Network Analysers (VNA) at sub-millimetre (sub-mm) frequencies is the development of high performance harmonic mixers, which have good conversion efficiency, flat frequency response, and stable characteristics to allow unchanging calibration. These specifications can be achieved with mixers having the following characteristics:

1) Low Harmonic Number

Many harmonic mixers for sale today were designed more than 25 years ago, when the maximum Local Oscillator (LO) frequency was usually less than 6 GHz. This severely limits performance, as a very high harmonic number is required to reach sub-mm frequencies. A key to our harmonic mixer results is keeping the harmonic number low, which implies a high LO frequency. Modern VNAs and spectrum analysers have internal oscillators which often exceed 15GHz and are much better suited for high frequency extender use. A low harmonic number allows a very uniform conversion efficiency curve, which is less prone to LO power or temperature variations. For extremely high frequencies, the harmonic number of the mixer can further be reduced by multiplying the LO before use in the harmonic mixer. This is nowadays quite simple, with a large range of GaAs MMIC devices to provide multiplication and amplification. We can, for example, pump a 800GHz mixer using the 8th harmonic (at 100GHz) and employ a x6 multiplier (16.67GHz initial LO frequency). Such a system is usually packaged as a module which includes all additional amplifiers, multipliers and power supplies.

The small insert photo on the left shows such a receive system, in this case allowing the 110-170GHz waveguide band to be covered but using only the 4th harmonic at the mixer by providing an additional x4 for the externally applied LO. This enables better performance to be achieved than using x16 directly.

2) Good Input Match

All harmonic mixers using a harmonic more than 4 (including the latest ones developed here) have a terrible RF input return loss of typically -2 to -4 dB. This is often compensated for by fitting the harmonic mixers with lossy absorbing material, but is accompanied by a loss in sensitivity and performance unrepeatability. Our approach is different; instead of using an absorber, or another lossy device, we fit each harmonic mixer with an RPG-made full-band, low-loss Faraday rotation isolator, (based on [4]), fitted as close to the mixer as possible. This solves the problem of the input return match as well as providing a good termination for unwanted harmonic signals generated at the mixer. Return loss is maintained at better than -16dB and the behaviour of the harmonic mixer is now entirely decoupled from the input waveguide flange match. Calibration data is provided for the mixer plus isolator combination and can be applied with high accuracy.

3) Control of Harmonics

In the design of the Agilent 11970 harmonic mixer, HP engineers discovered just how severe a problem unwanted harmonics can be [5]. We have already spoken about unwanted harmonics in the input waveguide in *2)* but harmonics also travel back down the LO port. Controlling how these frequencies are terminated is similarly critical to producing a mixer with a flat frequency response. We use balanced designs for all the mixers which have many advantages, including cancellation of LO amplitude noise in the IF. The balanced design also means that the *even* LO harmonic components remain in a "virtual loop" in the anti-parallel diode and mix with the incoming signal. No filtering of any sort is required for the even harmonics.

The *odd* harmonic RF currents however do not cancel in the anti-parallel diode pair, but are strongly generated and travel away from the diodes. The third harmonic is especially strong and needs proper termination. This is of course rather difficult to achieve in practise as the stripline circuitry must be small for the high input frequency but large enough to create a 3rd harmonic filter (at a very much lower frequency). If the substrate is made too wide or thick, it starts to exhibit narrow-band 'substrate' modes which cause unpredictable behaviour. We have used a combination of stub-filters and new, photonic-band gap (PBG) filters to achieve extremely wideband filters in a very compact form, such that the reflections of the 3rd and 5th harmonics do not have enough electrical length to cause interference problems, but realised on quartz, with dimensions that are appropriate for the high input frequency.

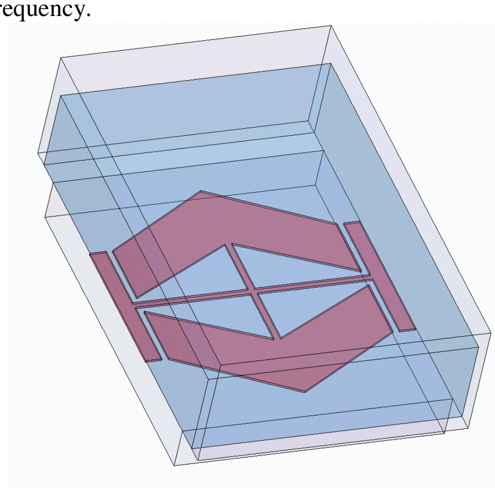

Fig 1 HFSS model of "PBG" low-pass filter

The filter structure illustrated uses a quartz substrate, with dimensions of only 180um wide x 160um long x 35 um high; unusually small for a 200GHz LPF. A transmission and reflection plot of this design is shown in Fig 2.

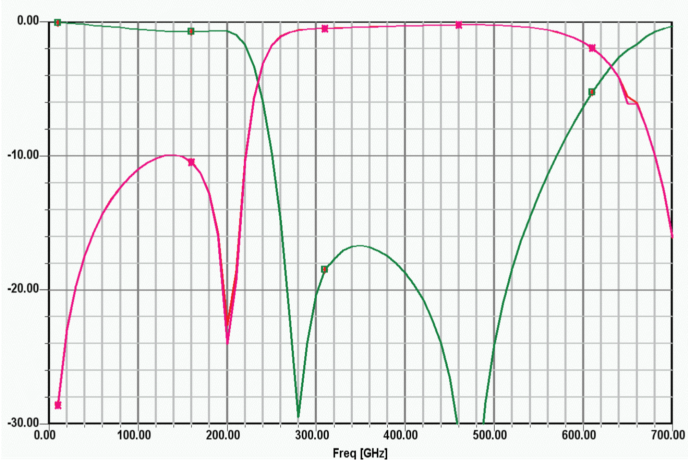

Fig2 S21(red) and S11(green) plot of Fig 1 (dB scale)

4) Novel Waveguide Transition Structure

To keep electrical lengths to an absolute minimum on the RF input side of the diode pair, a modified version of a standard rectangular waveguide to stripline transition (using a paddle probe extending approximately ½ way into the waveguide) was used. The design easily covers a whole waveguide band.

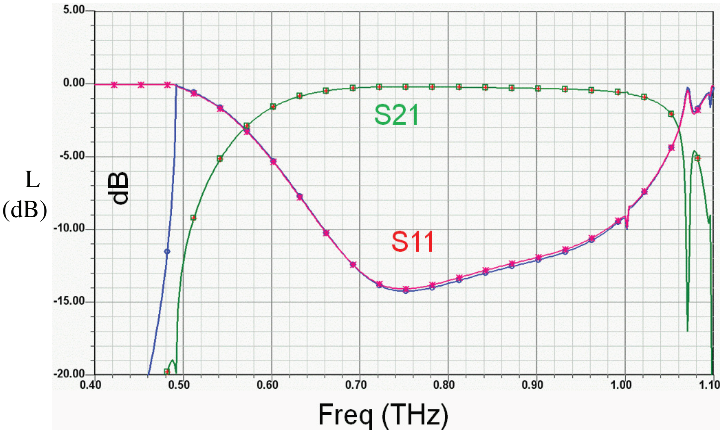

Fig 3 HFSS simulation of performance of the transition.

This transition has the new feature of a bond-wire forming a short to the waveguide back-short wall. The design is extremely tolerant to the dimensions of the short and there is an added advantage that the waveguide is not reduced-height. The short is necessary to drive the diodes against a ground for the LO frequency.

5) Anti-parallel Diode Redesign

Anti-parallel diodes which have low parasitic reactance are critical to providing good performance at high frequencies. Keeping junction capacitance (Cj0) down is also important to maintain a low conversion loss. The dependence of conversion loss (L) on Cj0 in an anti-parallel mixer has been previously studied [6].

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Unfortunately, all the presently available anti-parallel diodes for general sale have too high a value of Cj0 and too high parasitic reactance for high-performance use much above 300GHz. They are also physically too large to fit on strip-line substrate which is appropriate for 900GHz.

We have two collaborators: RAL and ACST, who have independently fabricated GaAs anti-parallel diodes that are of a new design, suitable for mixer use up to near 1THz. Two different approaches have been applied to the parasitic reactance question, both of which have been proven to work extremely well for harmonic mixers. In both cases, a key feature is reducing the parasitic capacitances of the diode, but also reducing the *inductance* of the beam-lead anode fingers, which we believe has been slightly overlooked in previous anti-parallel diodes. Details of these two diode designs will soon be released by the manufacturers (ACST GmbH Germany and SFTC RAL, UK)

6) Design Method

Designs were created and analysed using a mixture of Ansoft HFSS and AWR Microwave Office. HFSS is used to model the 3-D structure and diodes. An S-parameter file is then exported to Microwave Office for non-linear harmonic balance analysis. Accurate simulations are extremely tricky due to the high harmonic content and harmonic interactions.

III. RESULTS

TABLE I

Freq (GHz)	Harmonic Mixer parameters		
	Harmonic number	**max/min Conversion loss (dB) SSB**	**LO power**
26.5-40	3 *	13dB to 17dB	+13dBm
75-110	8	16 to 26dB	+15dBm
75-110	6	15dB to 25dB	+15dBm
75-110	7 *	18dB to 27dB	+10dBm
110-170	12	24dB to 35dB	+14dBm
140-220	16	30dB to 42dB	+12dBm
220-325	16	32dB to 50dB	+11dBm
400-560	6**	25dB to 35dB	+12dBm
650-780	8**	39dB to 43dB	+12dBm
680-780	10**	45dB to 50dB	+12dB
810-835	8***	24dB	+10dBm

*Indicates a cross-bar mixer, operation on ODD harmonic
** Unit sold by RPG includes a x6 active multiplier
*** Narrow band unit optimised for 820GHz

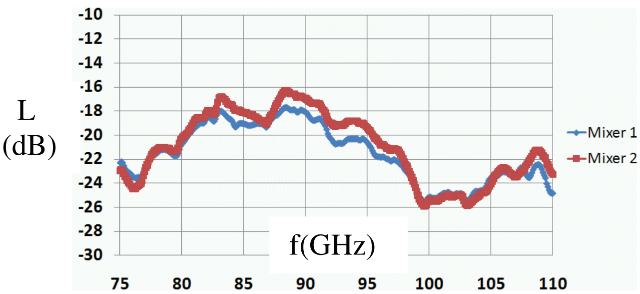

Fig 4 Conversion Loss (L) measurement of two mixers (WR10 mixer, 8th harmonic). Data point every 0.1GHz

Fig 4 shows high frequency resolution measurements of two, identical WR10 (75-110GHz) harmonic mixer, using the 8th harmonic. The conversion efficiency is good (-20dB on average), shows minimal structure and the mixer-to-mixer performance is very repeatable.

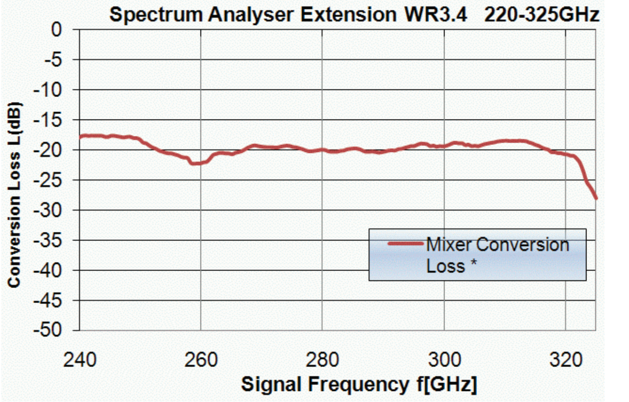

Fig 5 Conversion Loss (L) measurement of a WR3.4 mixer using the 4th harmonic, showing remarkably flat response.

All conversion loss curves for normal products can be viewed on RPG's web site, under "New Product line: Spectrum Analyser solutions" [7].

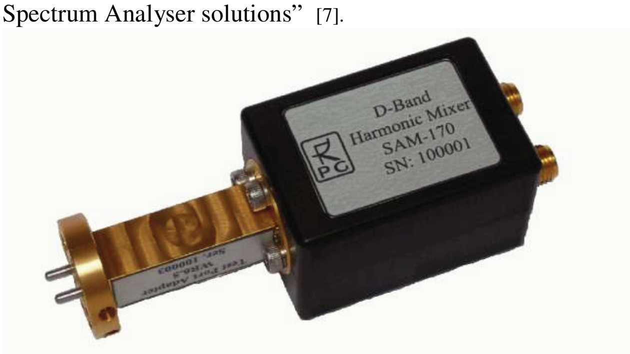

Fig. 6 A packaged harmonic mixer includes a replaceable waveguide test-port adaptor, an internal isolator and a LO/IF diplexer. IF and LO have separate SMA connectors.

These new mixers in table 1 show excellent performance compared to previous designs. Especially good is the result at 820GHz which is, however, narrow band and highly optimised. The 820GHz mixers have been built into an array.

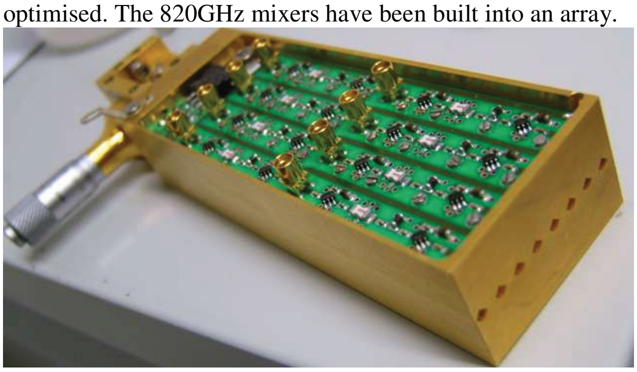

Fig 7 Packaged 820GHz harmonic mixers with feed horns, IF amplifiers and common WR10 LO port.

Using the previous generation of anti-parallel diodes in the 820GHz mixer, conversion efficiencies of around -45dB were obtained for a similar setup, so the new result shows a 20dB improvement! This conversion efficiency is exceptionally good given the frequency, and is very important for achieving a good dynamic range. The 820 GHz mixer is intended for use in a 32-element FMCW radar array for the examination of closed containers with a fast frame rate of 10 f.p.s. (project TERAcam). It is quite easy to integrate these mixers into a linear array and feed them with a common, high power LO source. Fig 7 shows a photo of eight such mixers in a working, stackable system, with a common WR10 LO input, ready for integration.

The rest of the harmonic mixers are designed to cover an entire waveguide band and some compromises have been made for bandwidth. Mixers up to 900GHz have been designed and are in the process of being tested. Testing is presently hampered by the unavailability of test equipment, calibration standards and wideband test sources.

These new mixers and wideband sources (also newly developed at RPG) are integrated into the latest Rohde & Schwarz VNA ZVA-Z series extenders and provide excellent dynamic range, calibration stability and accuracy. With two extenders (Fig 8) a complete set of accurate S-parameters can be measured, with a dynamic range of > 110dB (10Hz bandwidth) across the entire WR10 waveguide band.

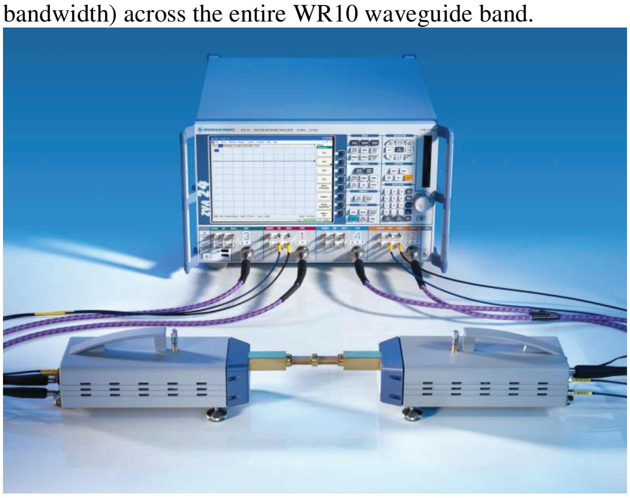

Fig 8 Rohde & Schwarz ZVA-Z110 VNA setup for WR10.

IV. SUB-HARMONIC MIXERS

It is also possible to use these new, low-parasitic antiparallel diodes in "normal" sub-harmonic mixers (LO is ½ the RF frequency). The results of early tests are very encouraging. For the highest frequencies, this has required a slight re-design of the existing mixer blocks, as the electrical length of the new-style anode beam-leads is significantly shorter than the older diode (less phase shift). The transmission line path length on both sides of the diode therefore had to be slightly lengthened to compensate and bring the design back to the optimum point. Tests at 424GHz and 660GHz have been made with the following results:

TABLE II

Freq (GHz)	**Sub-Harmonic Mixer parameters**		
	Tsys	**Conversion loss (dB) DSB**	**LO power & diode type**
410-450	1700K	7.2dB	5mW ACST
650-670	2400K	8.0dB	4mW ACST

Tsys is calculated directly from Y-factor measurements, without any extra corrections, so it also includes losses of waveguide and horn as well as the IF amplifier noise contribution. The 660GHz measurement is especially good, and uses a novel waveguide transition. Three 660GHz mixers with similar performance have been manufactured, with consistent Tmixer of around 1700K.

V. CONCLUSIONS

Using new diodes and careful mixer design, the performance of harmonic mixers at sub-mm wavelengths has improved substantially. There are still challenges to be overcome, including the design and production of low-loss, wideband isolators, directional couplers, wideband sources and calibration methods at the highest frequencies. However, big improvements have already been made. Many of these new components are being used to construct new ranges of test equipment, including spectrum analyser and Vector Network Analyser extenders, offering previously unavailable performance, stability and dynamic range.

ACKNOWLEDGMENT

This research and development has been possible with funding from Rohde & Schwarz, and for the diodes with funding from ESA-ESTEC. Realisation of the mixers and the new form of the diodes owes much to separate discussions between Byron Alderman (RAL), Oleg Cojocari(ACST) and Hugh Gibson. Both ACST and RAL plan to market these new diodes, so they should soon be available for purchase. Much of the design work was influenced by papers of J. Hesler and T. Crowe of Virgina Diodes, Charlottesville, VA USA and Neal Erickson of UMASS USA. Harmonic mixer design was assisted by previous papers of HP/Agilent [5].

I would also like to acknowledge the craftsmanship of Achim Walber, Jan Oelrichs, Marko Schwarze and Ralf Henneberger, the fine-mechanic team at RPG lead by Marc Warnke and the wealth of experience of Ralph Zimmerman.

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