Sub-millimeter-wave balanced mixers and multipliers at the 5th harmonic

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***Abstract*— Balanced 3rd harmonic multipliers and mixers have been successfully realized for many years using anti-parallel and series-connected Schottky diodes respectively. It is in principal possible to use the same techniques to make sub-millimeter wavelength devices using the 5th harmonic as the design should be similar. This work will discuss the problems involved with the designs of a WR2.2 wideband balanced 5th harmonic mixer at 500 GHz and a WR2.2 balanced quintupler multiplier also at 500 GHz. Simulations and test results are shown. The efficiencies of 5th harmonic devices are understandably significantly lower than 3rd harmonic devices, but the 5th harmonic allows an attractive, direct way to 500 GHz from the relatively easy 100 GHz where MMICs are nowadays readily available.**

***Index Terms*—Quintupler, Harmonic-mixer, 5th harmonic, WR2.2**

I. INTRODUCTION

NARROW-BAND multipliers and mixers at the 5th harmonic have been available for many years but there are very few wideband designs or designs with reasonable conversion efficiencies. The problem of 5th harmonic generation and filtering is similar in both harmonic mixers and multipliers, so there is much in common between the two design concepts. Section II will review a multiplier design and section III will review a harmonic mixer design. The use of commonly available European diodes is a key to both designs. ACST GmbH Germany and Teratech Ltd UK have made custom-designed diodes for RPG and GMD with special high-frequency features which are critical to the successful realization of conventional mixers and also to these 5th harmonic designs at 500 GHz. Both multiplier and mixer designs use pairs of Schottky diodes in predominantly balanced, varistor mode configuration. This has many advantages, including suppression of even harmonics and (for the multiplier) isolation between input and output ports.

The general aim of this paper is to provide some background information on successful wideband 5th harmonic designs and the problems encountered, as there is very little in press about such attempts. Many people have considered such 5th harmonic designs but very few have published data. We hope to cover the design issues and present data of working devices. The performance of these designs is considerably worse than 3rd harmonic designs but we found it interesting that wideband 5th harmonic designs are indeed possible and also to compare performance with 3rd harmonic designs and measurements.

II. MULTIPIER (QUINTUPLER)

Efficient x5 multiplier designs require very specific impedances at the input, output and idler circuits which are not easy to synthesize. Providing these impedances for the idlers and coupling circuits is a major challenge and is considerably more difficult than for a 3rd harmonic design. Most previous efficient x5 multiplier designs have used series connected devices or HBVs (Heterostructure Barrier Varactor). Various groups have successfully made narrow-band designs, including Chalmers University [7] and University of Virginia [8]. In contrast, we want to concentrate on making full waveguide-band devices.

We have used anti-parallel diodes because they generally have less severe impedances than a pair of series-connected diodes, which is beneficial for a wideband design, even though the overall efficiency may not be as high. Anti-parallel diodes are also widely available for sub-harmonic mixer use and generally have lower parasitic reactance than series-connected designs and are also slightly easier to solder.

Our x5 multiplier design is based on an existing x3 multiplier. A key part of the design is the efficient blocking of the strong 3rd harmonic in both input and output circuits. For a WR2.2 full-band design, this requires a filter with steep rejection below 300 GHz (highest 3rd harmonic frequency), but passing 325 GHz (lowest 5th harmonic frequency). Such a filter is tricky to realize and many different types were tried. Low loss is critical, as is simplicity. The solution finally chosen for the RF output is to use a shorted-stub type bandpass filter, with capacitive loading on the resonators.

Gibson Microwave Design EURL (GMD) was founded in 2009 and is based in Antony 92160, France. GMD is a one-man company and provides significant design assistance. Contact gibson@radiometer-physics.de

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Advanced Compound Semiconductor Technologies (ACST GmbH) is a spin-off company from TU Darmstadt. ACST produces high frequency diode technology for mixers, multipliers and photodiodes. Contact contact@acst.de or www.acst.de for further details.

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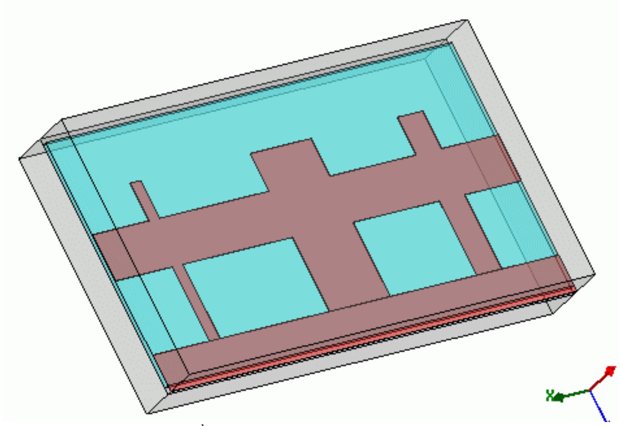


Fig. 1. 3D model of the 5th harmonic shorted-stub bandpass filter.

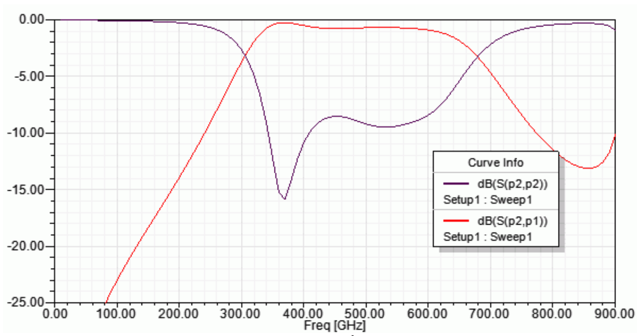


Fig. 2. S-parameter plot (dB scale) of the 5th harmonic bandpass filter.

The filter is further optimized to suit the impedances of the multiplier. The design is low loss, simple and small. It succeeds in passing the 5th harmonic, while terminating the 3rd harmonic with a low impedance with short electrical length which improves efficiency and gain flatness.

For the input circuit, a simpler filter based on low-pass hammer-head filters and stubs is used.

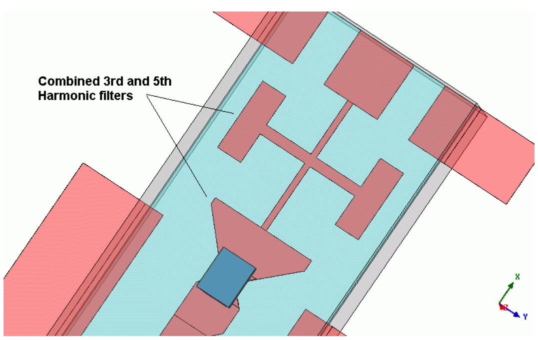


Fig. 3. RF input filter design, with wideband LPF rejection.

Again, it is paramount to block unwanted harmonics as near to the diode as possible to limit the electrical path-length of reflections, which can cause large dips in the multiplier efficiency.

The final design is quite similar to an earlier HBV narrowband quintupler [1] which can be found in the literature.

The simulation uses the conventional approach of pairing a linear structure simulator and a non-linear harmonic-balance simulator. The entire device is simulated with no division of frequencies, and exported as a single S-parameter block so that the complex interactions of the many harmonics could be correctly simulated within the harmonic balance simulator up to the 7th harmonic.

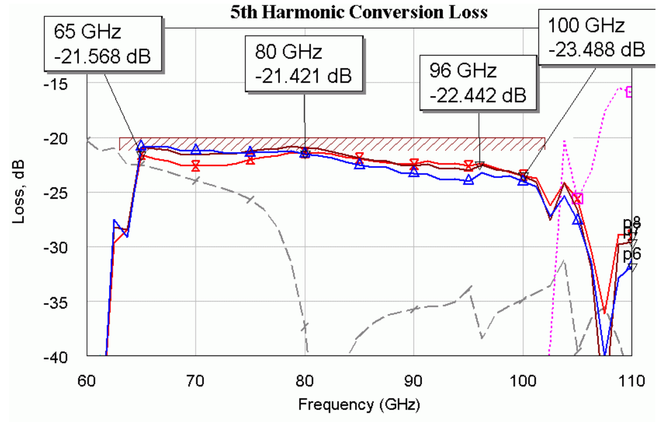


Fig. 4. Simulation of the 5th harmonic multiplier The thick curves are conversion efficiencies with varying input powers. The pink dotted line is the unwanted 3rd harmonic at the output and the grey dashed line is the 3rd harmonic leaking back into the input.

Fig 4 shows the simulation results of the multiplier. The unwanted 3rd harmonic signal (pink, dotted) is successfully rejected below input frequencies of 100 GHz (i.e. 500 GHz, or top of the WR2.2 band) as required. The conversion efficiency is not strongly dependent on LO power and the conversion plot is remarkably flat. For good efficiency, it is important to use high LO pump powers, and the diode current conduction angle should to be quite large.

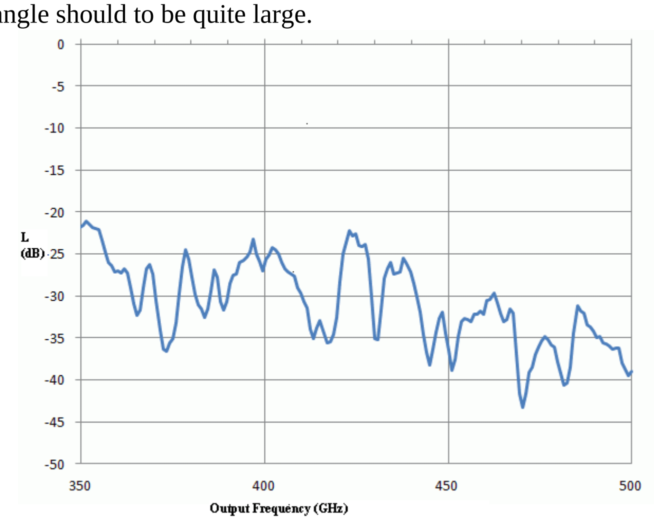
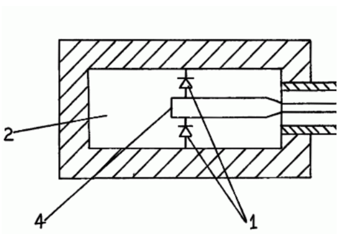


Fig. 5. Measured 5th harmonic multiplier conversion loss (dB).

The 5th harmonic multiplier was fabricated and measured by RPG. Fig 5 shows the measured (uncorrected) conversion loss (dB scale) against output frequency (GHz). The measurement and simulation are in reasonable agreement but there are rapid variations in power, in excess of 10 dB which is unaccounted for in the simulation. Some of this is undoubtedly output mismatch and has a characteristic periodic structure. Nevertheless, a useful multiplier design was successfully achieved with moderate efficiency over the entire WR2.2

band, which was easily pumped from a wideband 100 GHz source.

III. MIXER (USING 5TH HARMONIC)



Balanced mixer designs are possible at odd harmonics, using a "cross-bar" mixer. This design is typically used for fundamental balanced mixer designs [2][3] as it has high intrinsic isolation from input and output due to the arrangement of the diodes. The small insert shows the general arrangement, with the diodes (1) in series across a rectangular TE10 waveguide (2) but appearing in anti-parallel to the co-axial TEM input line (4). Cross-bar mixers also work well at higher odd harmonics [6] but the higher harmonics are of course not isolated from the input, so extra filters need to be used. Even-harmonics are generated in the output waveguide (but no odd harmonics). The opposite happens (odd harmonics only) on the input circuit. The simplicity of this design has some shortcomings;- Because the diode is effectively the waveguide coupler, there is no opportunity to filter out the even harmonics before the waveguide, and the position of the diodes in the waveguide dictates a minimum length of input transmission line before input-filter components can be used (because of the length of the waveguide backshort).

We have previously made mixers at the 3rd harmonic using the cross-bar concept with good results [4] and others have at the 7th harmonic [6] so it seemed appropriate to adapt this design to try it at the 5th harmonic. Suitable series-connected diodes were available from two European sources, Teratech Ltd (UK) and ACST GmbH (Germany) both with very low parasitic capacitances and small size. An example of the Teratech "SC1" is shown below in Fig 6.

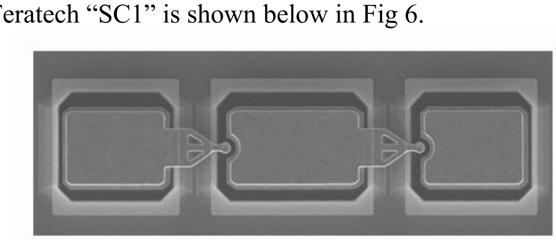


Fig. 6. Scanning Electron Microscope image of an "SC1" diode pair [ref?]

The design requires considerable filtering on the input circuit to reflect the unwanted harmonics close to the diodes. A combination of radial stubs, hammerhead and special photonic-bandgap filters [4] [5] are used to achieve the wideband filtering. The final design is similar to Fig 7. Considerable time is required for optimization of the various filters to achieve the desired results. Waveguide impedance transformations and filtering are also optimized in the output waveguide using stepped transformers and custom size cutoff waveguide. One can also see in Fig 7 that it is not possible to easily fit filters close to the diode, where they would be ideally situated.

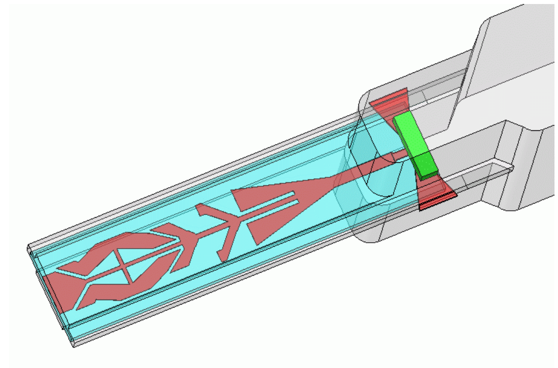


Fig. 7. 3D model of a generic 5th harmonic mixer for the WR2.2 band.

Very high accuracy in the 3D model and simulation are required to achieve results that are realistic at the 5th harmonic. The harmonic balance simulator must be capable of accurately simulating the multiple combination of mixing products. The APLAC HB solver in Microwave Office (AWR Corp) is used for these simulations.

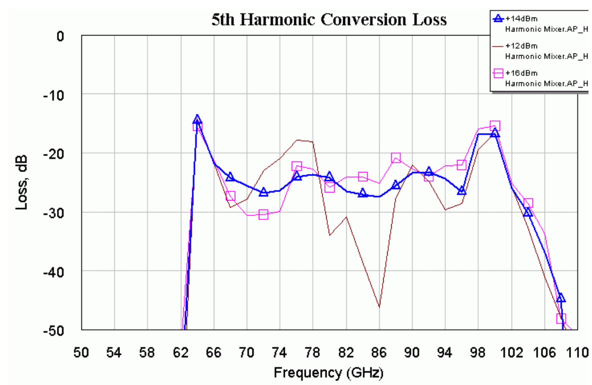


Fig. 8. Simulation of Conversion loss of 5th harmonic mixer (dB) against LO input frequency. Plots show different input LO powers: Blue +14dBm, Brown +12dBm and Pink +10dBm.

The simulated WR2.2 Mixer conversion efficiency (dB) is plotted in Fig 8 against LO input frequency. The mixer is quite flat from 65 to 100GHz input frequency (325 – 500GHz at 5th harm) but is quite sensitive to the LO power level.

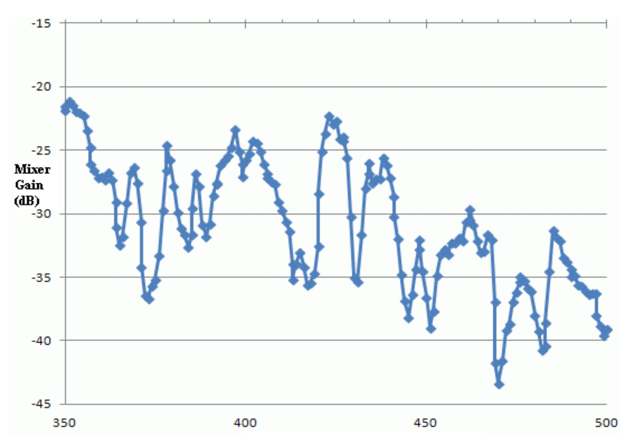


Fig. 9. Measured Conversion Loss (dB) against RF output frequency (GHz)

The measured conversion efficiency in Fig 9 is quite similar to the simulation, with the exception of a drop off in performance above 450 GHz which needs further investigation. There is also more variation in the conversion than the simulation but the overall performance is generally as predicted.

IV. CONCLUSIONS

Wideband varistor-type Quintupler (5th harmonic multipliers) can be designed using anti-parallel Schottky diode pairs but efficiencies are expected to remain around 1%. The input match is good, but high pump power is necessary to produce the best efficiencies and flattest response. Biasing high harmonic devices (mixers and multipliers) seems to be of limited value, as a fast 'snap' turn-on is essential for efficient, high harmonic generation.

For multiplier designs using anti-series diodes (or HBVs) input impedance match seems to be the main limitation (being both high-Z and reactive). HBVs are usually very narrow band (5%), but can be relatively efficient.

Using anti-parallel diodes allows an easier impedance match and varistor-type multiplier designs but overall efficiency is lower.

Harmonic mixers at the 5th harmonic, using cross-bar technology work well, but conversion efficiency is dependent on the level of 5th harmonic generated, which can be quite variable with frequency.

Designs for wideband multipliers and mixers are possible, but the design effort required is very considerable compared to 3rd harmonic designs. Control of the strong lower (3rd) harmonic reflections is critical for a flat response and in some cases, small amounts of attenuator damping are necessary to achieve a flat conversion efficiency response.

ACKNOWLEDGMENT

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