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Compact Broadband MMIC Schottky Frequency Tripler for 75 – 140 GHz

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Abstract—**In this paper a monolithically integrated frequency tripler based on an antiparallel pair of Schottky diodes is presented. The tripler is designed for flat output power response and wide frequency range. With 2 mW of input power the tripler covers the frequency range of 75 – 140 GHz (bandwidth 60 %) delivering output power between -19.4 dBm and -14.7 dBm with an average efficiency of 1.1 %. The efficiency of the tripler stays almost constant in a wide input power range. With the largest available input power level of the test setup, 17.1 dBm, the tripler output power is -2.4 dBm and efficiency 1.1 % at 75 GHz, and the output is not yet saturated. The input and output matching and filtering circuits are optimized to minimize the chip dimensions. The total chip area including RF and bias probe pads is only 0.47 mm^2. The state-of-the-art results are achieved in the small size of the chip as well as in the wide frequency bandwidth.**

Keywords-component; Schottky diode, antiparallel diode pair, frequency tripler, broadband operation

I. Introduction

Frequency multipliers are key components in most millimeter wave systems because availability of low-noise fundamental sources with the capability for frequency sweeping is scarce. Traditionally, the Schottky diode has been the device of choice for the multiplying element and it is still the most common multiplying element available at millimeter wavelengths [1] - [4]. Recently, multipliers based on, e.g., heterostructure barrier varactors [5], [6] (HBV) or on metamorphic high electron mobility transistors [7], [8] (HEMT) have developed rapidly. HBVs reach very high efficiencies and output power levels but are inherently narrowband devices. HEMT-based active multipliers provide very good conversion efficiencies and can be implemented on the same chip with amplifier elements. A disadvantage with active devices is that they cannot usually handle large input powers and are not as stable as passive multipliers.

Schottky-based multipliers can be divided into reactive (varactor diodes) and resistive (varistor diodes) multipliers. Mixed mode operation is also possible. Varactor multipliers have larger efficiencies and produce more output power than multipliers based on resistive Schottky diodes. Resistive multipliers on the other hand have smaller capacitance variation and thus can be designed to cover wider bandwidths than varactor multipliers.

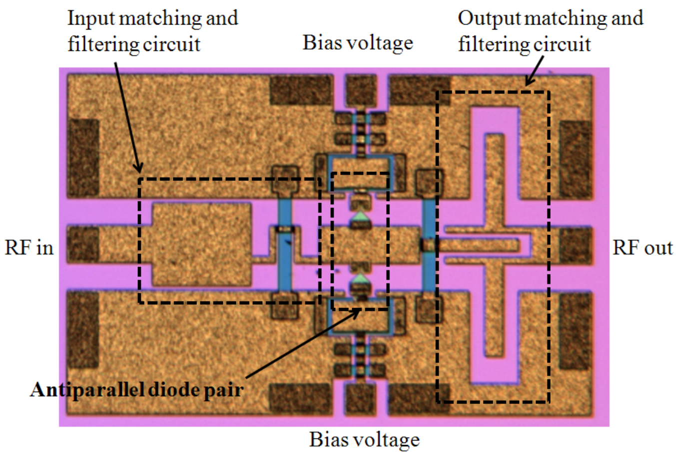

Figure 1. Microscope photograph of the measured tripler circuit.

In [3], a full W-band MMIC frequency tripler is designed using a commercial BES process by United Monolithic Semiconductors with an average conversion efficiency of 1.5 % and a chip size of 1.48 mm^2. In [4] a W-band MMIC tripler is designed using a GaAs PHEMT process and uses gates of the HEMT transistors as diodes. This design has a measured conversion loss of 18 – 20 dB at 87 – 102 GHz and does not need bias current. The chip size of the design is 1.5 mm^2.

In this work we present the design steps and show simulation and measurement results for an MMIC tripler covering two overlapping frequency bands, W-band (75 – 110 GHz) and F-band (90 – 140 GHz), offering a 60 % operational bandwidth with an average efficiency of 1.1 %. The tripler uses compact input and output matching and filtering circuits reducing the overall chip area to 0.47 mm^2, which is one third of the chip size compared with designs of comparable performance at W-band [3], [4]. To the authors' knowledge these are the first reported results for a MMIC Schottky frequency tripler covering two overlapping millimeter wave frequency bands.

II. CIRCUIT DESIGN

A microscope photograph of the tripler is shown in Figure 1. The tripler is fabricated on a 625 µm thick gallium arsenide (GaAs) wafer using UMS BES Schottky diode process and 1 x 3 µm^2 diodes, as the design in [3]. After the front side fabrication, the 625 µm thick chip was thinned to 100 µm to suppress the possible surface wave modes (BES process standard thickness is also 100 µm but for research purposes thicker substrate was delivered and thinned in post-prosessing). The dimensions of the tripler circuits are 0.85 x 0.55 mm^2 and the total area including the RF and bias probe pads is 0.47 mm^2. The tripler consists of input and output matching circuits, separate bias routes for both diodes and of an antiparallel diode pair. In order to suppress the coupled slotline mode and to obtain a symmetrical coplanar mode, the circuit was designed to be as symmetric as possible and the coplanar ground planes were connected by metal lines beneath the passivation layer (shown in blue in Figure 1).

The antiparallel diode pair is well suited for a broadband tripler as the even harmonics of the input signal are trapped in a virtual short circuit formed by the diodes and suppressed [9]. The input and output circuits must fulfill a demanding criteria. First, the circuits must obviously let the wanted signal to pass and second, to provide a reasonably large reactive load at other frequencies. In addition, the circuit elements should be as small as possible to minimize the chip size and transmission line loss. In order to fulfill these requirements in the wide frequency range of 25 – 47 GHz in the input and 75 – 141 GHz in the output, unconventional circuit elements were designed using full-wave and quasi-static mode electromagnetic simulators Ansoft HFSS and ADS Momentum. For example, the output matching and filtering circuit consists of an open-terminated series stub in the center conductor [10] and in the same place (electrically and physically) two open-terminated parallel stubs. This structure is compact and fulfills the electrical requirements, but has no circuit model and, therefore, must be designed and optimized using electromagnetic simulators.

As the input matching circuit affects also the output matching and vice versa, the design is an iterative process. The process is time-consuming compared to design using only circuit simulator and mathematical models for passive components. However, the custom design using electromagnetic simulators has much more degrees of freedom and can provide better performance with less circuit area. The last step in the design was the electromagnetic full-wave simulations of the entire tripler structure with HFSS and the harmonic balance simulations with Agilent ADS circuit simulator, where the model for the diode junctions was coupled with the 3D-electromagnetic model from HFSS.

III. MEASUREMENT SETUP

For the measurements, the chip with the tripler circuit and some test structures was attached on a 10 mm thick piece of Rohacell Foam with a tiny drop of superglue. The chip with the tripler and the test structures is shown in Figure 2. A simplified schematic of the measurement setup is shown in Figure 3. Because of the wide range of frequencies used in the measurements, no single device could be used to provide the input signal or measure the output signal from the whole frequency band. For the generation of the input signal, Agilent signal generators E8257C and 83623B and Agilent Millimeter-

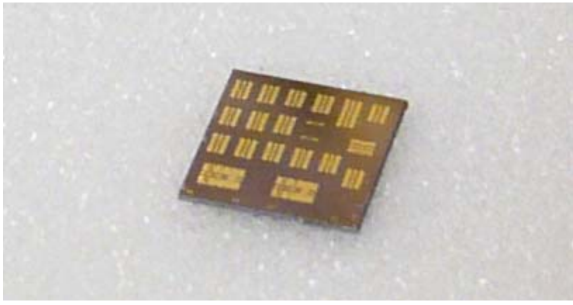

Figure 2. GaAs chip with the tripler and on-wafer test structures.

Wave Source Module 83556A were used. The input connection was done with an on-wafer probe with a 2.4 mm coaxial connector. The output power was measured with an Agilent E4419B Dual Channel Power Meter together with V8486A and W8486A power sensors, and with an Agilent E4407B Spectrum Analyzer at V-band (50 – 75 GHz) and W-band (75 – 110 GHz) using harmonic mixers 11970V and 11970W. Measurements at 110 – 153 GHz were done with an Erickson PM2 Power Meter. The connection to the output of the tripler was done using waveguide on-wafer probes for the V- and W-bands. The frequency range of 110 – 153 GHz was measured with a Cascade Microtech WR-06 waveguide probe. Before the tripler measurements, the losses of the probes were measured and calibrated out. The results presented in the paper are for the tripler chip alone. Three types of measurements were performed.

1. Wideband measurements at 51 – 153 GHz with 2 mW of input power
2. W-band measurements with 2 mW, 5 mW, 10 mW, and 20 mW of input power
3. Compression measurement up to 51 mW of input power at 25 GHz

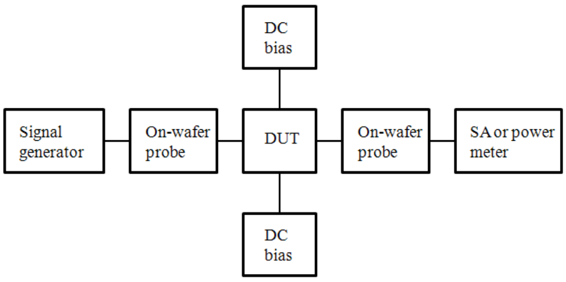

Figure 3. Simplified schematic of the measurement setup.

The wideband measurements were done with only 2 mW of input power as this was the largest input power available across the input frequencies of 17 – 51 GHz. The bias voltage was optimized for every level of input power and kept constant during the frequency sweep. For the compression test, the input frequency of 25 GHz was selected for the largest value of the input power available from the test setup. In the compression test, the bias voltage was optimized for every input power level.

IV. RESULTS

The output power of the tripler as a function of the output frequency and with the input power level of 2 mW is shown in Figure 4. The efficiency of the tripler with the same input power level is given in Figure 5. The maximum output power difference in the operation band of 75 – 140 GHz is 4.7 dB with the maximum of -14.7 dBm at 108 GHz and the minimum of -19.4 dBm at 129 GHz. The maximum efficiency is 1.68 % at 108 GHz and the minimum 0.58 % at 129 GHz.

Measurement results with the input power levels of 2 mW, 5 mW, 10 mW, and 20 mW at the W-band are shown in Figure 6. The output power level is flat across the W-band with all measured input power levels. The difference between the minimum and maximum values are 3.7 dB, 4.1 dB, 3.8 dB, and 3.6 dB with 2 mW, 5 mW, 10 mW, and 20 mW of input power, respectively.

The compression measurement at 75 GHz was done with the input power level up to 51 mW. The output power as a function of the input power is shown in Figure 7 and the corresponding efficiency of the tripler in Figure 8. The efficiency reaches 1.09 % with the input power level of 2 mW and stays between 1.09 – 1.18 % as the input power level is

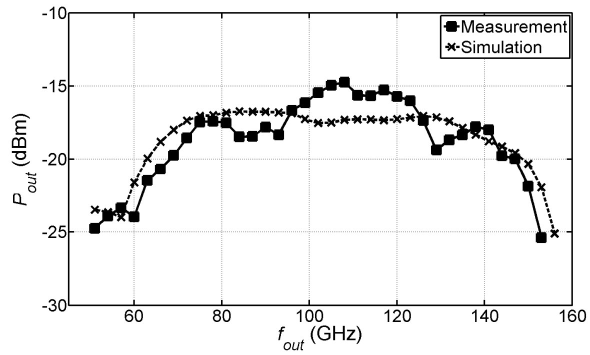

Figure 4. Output power of the tripler with 2 mW of input power across the frequency band of interest.

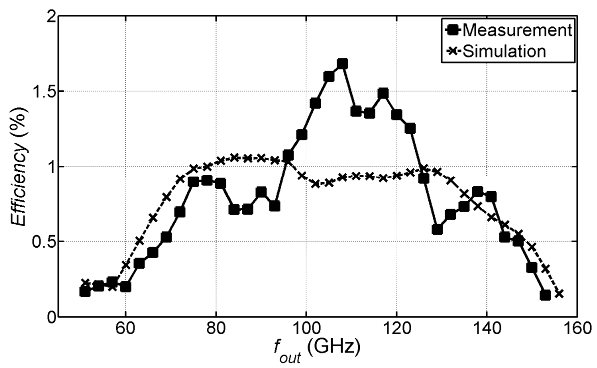

Figure 5. Efficiency of the tripler with 2 mW of input power across the frequency band of interest.

increased to its maximum value of 51 mW where the output power is -2.4 dBm and the efficiency 1.12 %. The tripler could not be saturated with the input power available from the test setup. In Figure 6. it can be seen that the efficiency of the tripler stays nearly constant at least up to 20 mW of input power across the W-band.

V. DISCUSSION

Since handling of signals at higher millimeter wave frequencies is usually done in the waveguide environment, most multipliers and other signal sources are usually designed to work within a certain waveguide frequency band or even at a spot frequency where they can provide high output power. However, in the measurement or characterization of some applications, such as THz imaging arrays based on wideband bolometer or Schottky diode detectors, or wideband antennas (e.g., bowtie or log-periodic), a frequency range exceeding standard waveguide bands is beneficial. These kind of measurements would benefit from wideband frequency sources such as the one presented in this work as the number of devices needed to cover the operational frequency range of interest for a certain application would be reduced. The coupling of power from the monolithic device to open air could be done, e.g., with an on-chip antenna combined with a lens antenna.

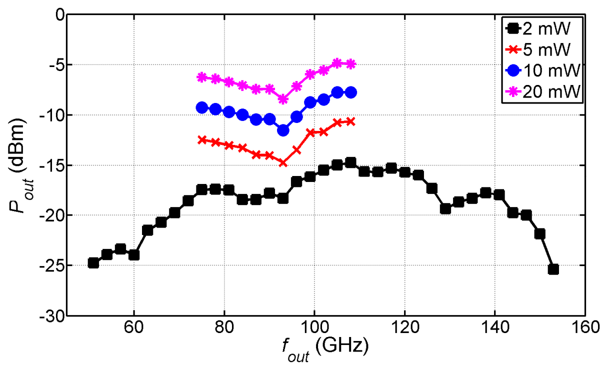

Figure 6. Measured output power with 2 mW, 5 mW, 10 mW, and 20 mW of input power. 2 mW was the largest input power level that was available throughout the whole frequency range and the higher input power measurements were performed only at the W-band.

One challenge in the design of wideband multipliers is the harmonics that occur at the wanted output band. The harmonic content was measured using spectrum analyzer in the V- and W-band. The 2^{nd} and 4^{th} harmonics are always more than 25 dB below the wanted third harmonic and are negligible in the total output power. However, the 5^{th} harmonic level was measured between 100 – 110 GHz with the input frequency of 20 – 22 GHz (the highest frequency of the harmonic mixer for the spectrum analyzer was 110 GHz) and was measured to be only ~10 dB below the third harmonic. This is a problem for the input frequencies of 25 – 28 GHz as they result in the wanted output frequencies of 75 – 84 GHz and in the 5^{th} harmonics at 125 – 140 GHz which lie in the tripler output band. W-band measurements were performed comparing the output power with the spectrum analyzer and with the power meter in order

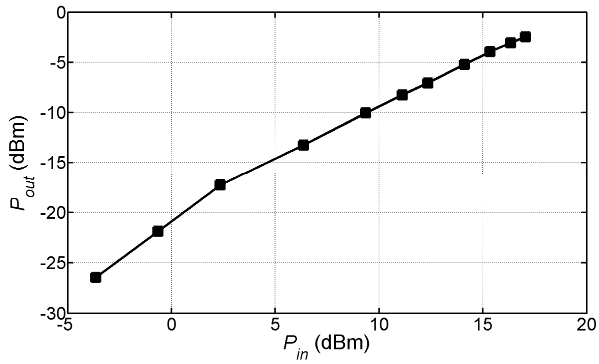

Figure 7. Output power at 75 GHz as a function of input power. The largest available input power level of the test setup was 17.1 dBm (51 mW).

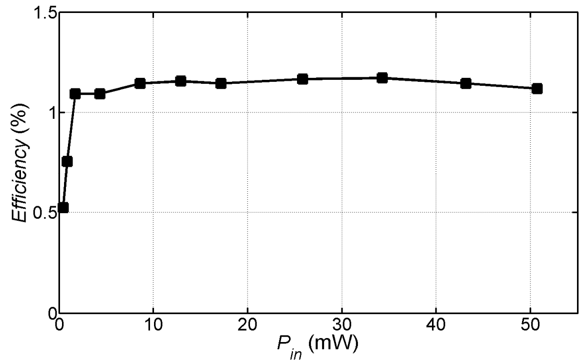

Figure 8. Efficiency at 75 GHz as a function of input power. The tripler is not yet saturated and the efficiency with largest available input power is almost the same as the maximum efficiency with 34 mW of input power.

to investigate the effect of the 5th harmonic in the total measured power. In the limits of the measurement accuracy no effect of the 5th harmonic could be seen. However, if very sensitive measurements are to be performed using this type of tripler as a source, the 5th harmonic content should be measured or the frequency range limited so that the 5th harmonic does not lie in the frequency band of interest.

VI. Conclusions

A monolithic Schottky frequency tripler covering the frequency range of 75 – 140 GHz (bandwidth 60 %) is presented. The tripler offers flatband response. The largest difference in the in-band output power level is 4.7 dB with the maximum of -14.7 dBm at 108 GHz and the minimum of -19.4 dBm at 129 GHz with 2 mW of input power. The maximum attained output power is -2.4 dBm at 75 GHz with the input power level of 51 mW. The output power level was limited by the available input power as the tripler was not saturated and was still operating at 1.12 % efficiency which is very close to the maximum efficiency of 1.18 % at 75 GHz. The tripler uses compact input and output matching and filtering circuits resulting in a chip area of 0.47 mm^2, which is one third of the area of previously reported full W-band MMIC diode tripler circuits. To the authors' knowledge, these are the first reported results of a monolithic frequency tripler to cover the full frequency range of two overlapping frequency bands, 75 – 110 GHz and 90 – 140 GHz.

Acknowledgment

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