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***Abstract*—A waveguide embedded 250 GHz HBV-varactor quasi-optical multiplier array is presented. The module utilizes a mechanically compact and simple shim system, combining the large array power handling capability with the convenience of waveguide interfaced circuits. At the same time this approach offers excellent power and frequency scalability. The current tripler prototype produces a non saturated output power of 8 mW at 248 GHz during initial measurements at medium pump power.**

I. Introduction

During the past decades considerable effort has been spent on increasing the output power and efficiency of sub-millimeter wave sources. This work focuses on varactor based multiplier sources whose general progress as well as competing technologies are well summarized in [1]. While sufficient power for single receiver LO drive is available in most of the THz spectrum, applications such as radar, communication links and large arrays of receivers call for an increasing amount of source power. Quasi-optical power combination has been successfully applied to e.g. amplifiers, [2], oscillators, multipliers and mixers, [3], at millimeter wave frequencies. The development of such array multipliers is challenging and not yet fully explored, important contributions to the field include [4] [5] [6] [7] [8]. However, no waveguide embedded quasi-optical multiplier arrays operating above 100 GHz providing fundamental waveguide mode output have been reported so far.

The recent progress of GaN W-band power amplifiers, [9] [10] [11], are pushing the upper limit of what conventional multiplier topologies can handle in terms of input power. Binary waveguide combiners in conjunction with the use of one dimensional diode arrays e.g the one presented in [12] is one way towards higher power THz sources utilizing the recent GaN amplifiers. But as the input power reach multi watt level the complexity, and loss, of the waveguide split and combine network increases. The advantage of using quasi-optical power combining is that the number of active devices can be scaled according to the available input power without affecting the combining efficiency.

The quasi-optical power combined varactor multiplier presented here, shown in Figure 1, is intended to serve as a technology demonstrator for future higher efficiency and higher frequency versions. It's still not fully evaluated at high pump powers due to the lack of a suitable amplifier but initial results are presented. The concept is scalable for higher power handling and higher frequency while offering less mechanical complexity for future THz sources.

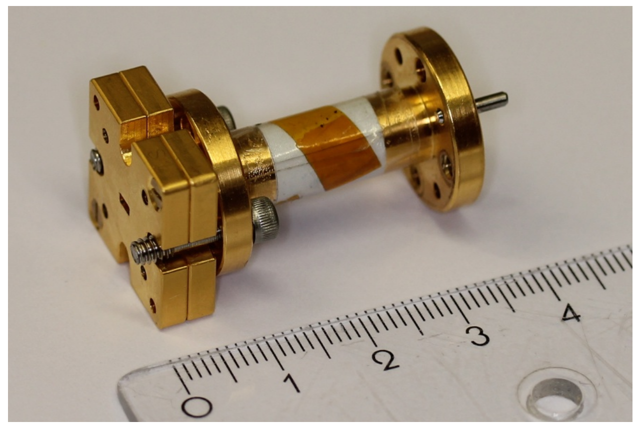

Fig. 1. Photo showing the compact two-shim system together with a standard 25 mm linear WR-10 to WR-03 taper.

II. Design

The multiplier array consists of a 72 element HBV tripler configured as 6 by 12 dipole unit cells. Each 20 um^2 HBV diode, [13], contains six serially connected barriers fabricated on an 3 barrier epitaxial structure adopted from [14]. The multiplier was modeled as a unit cell using a combination of transmission line theory, the induced EMF method [15], [16], and numerical finite element frequency domain models. A representation of the unit cell is shown in Figure 2. The multiplier module layout consist of, starting from the input side, a 380 um thick InP matching plate, the dipole array on the 200 um varactor substrate and a bandpass filter surface on 150 um quartz. The outer array dimensions are 2.54x1.27 mm^2, thus matching a standard WR-10 waveguide. On the output a WR-10 to WR-3 linear taper is used to produce a TE10 fundamental mode interface on the output. It was predicted in [17] and shown in [18] that for similar conditions as used in this work as little as 2 % of the generated third harmonic power will propagate towards the input due

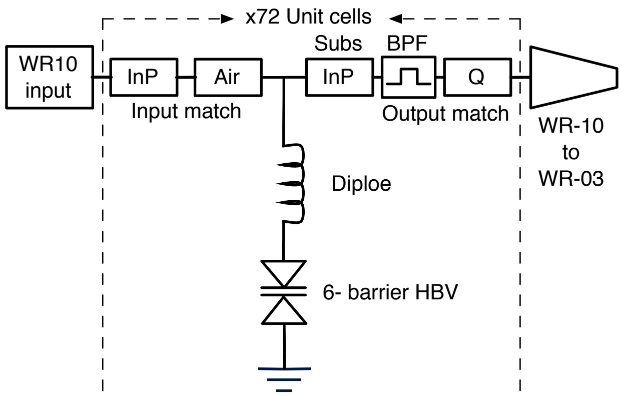

Fig. 2. Transmission line model of a unit cell multiplier

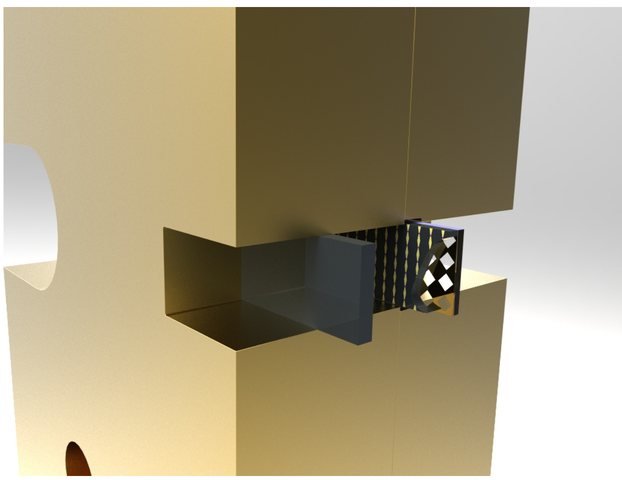

Fig. 3. Cross section model of the two mounting shims showing the structure of an assembled module. From left to right: The input matching slab, the varactor array and finally the filter surface on the quartz substrate stack.

to the dielectric difference between the front (Air) and back (InP) of the antenna array. Thus no filter is used at the input to reflect the third harmonic signals propagating towards the input, simply because the insertion loss would be higher than the power gained.

One drawback of placing the array in a TE10 mode waveguide is the non homogenous pump power distribution. The power density varies as $sin(x)^2$ along the broad waveguide dimension. This results in unequal power division among the dipole rows and hence a varying conversion efficiency. Summing different harmonic balance simulations together the expected module conversion efficiency at 83 GHz and 700 mW input is approximately 5 %.

A. *Mechanical housing*

By using mechanically simple mounting shims to house the multiplier components the machining complexity can be reduced. More mechanically advanced waveguide power-combining circuits utilizing 3-dB branch-line couplers or Y-junctions typically requires end mills with an aspect ration in the range 2:1 to 4:1. As the frequency increase such tooling becomes increasingly expensive. In the shims used here the minimum tool diameter is set by the pocket corner radius, a non critical design parameter.

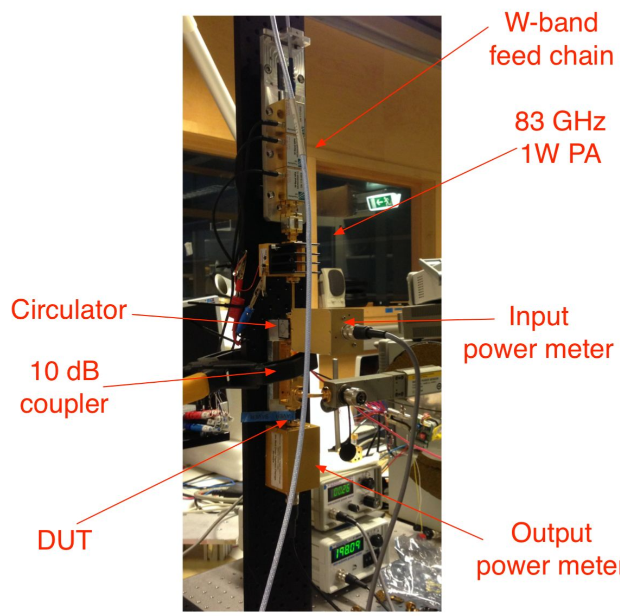

Fig. 4. The measurement system used for testing the multipliers output power and conversion efficiency.

The current prototype consist of two shims. The first one holding the InP input matching circuit at the correct distance from the array front. The second shim houses the array and output filter stacked together. A thermally conductive compound is used around the array edges to enhance the heat transport to the metal block and hold the array-filter stack in place. In Figure 6 the array mounting shim is shown together with an HBV-array, quartz filter circuit and an additional 50 um thick quarts spacer. The spacer is added since the filter was fabricated on a 100 um quartz substrate. A cross section model of the assembled mulitplier module is also shown in Figure 3.

III. Measurement results

The module was tested using a 1 W, 83 GHz, GaN power amplifier as pump source, the measurement system is shown in Figure 4. Due to circulator losses the maximum available power to the tripler module was 860 mW. Figure 5 shows the output power and conversion efficiency respectively with the amplifier driven into saturation. The two series, dashed and solid line, represent two tests with slightly different matching circuits. A maximum output power of 8 mW has been measured at 248 GHz and a drive level of 850 mW. The measured output power is not compensated for loss in the WR-3 to WR-10 taper and 100 mm waveguide, approximated to 0.8 dB total, associated with the calorimetric power sensor used. A maximum conversion efficiency of 0.95 % was achieved at 248 GHz and 8 mW output power. During the tests the conversion efficiency was monotonically increasing with increasing input power.

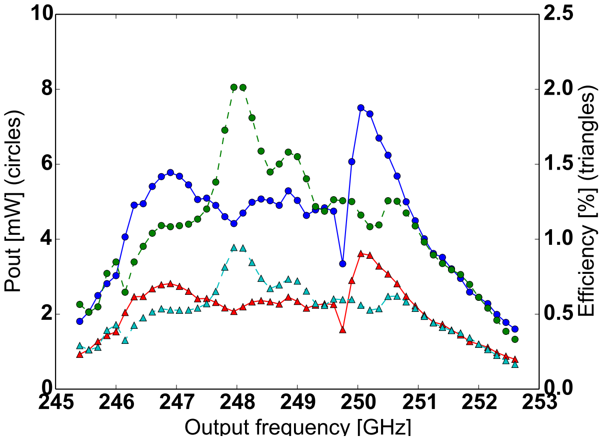

Fig. 5. Measured output power and efficiency as a function of frequency for two slightly different matching networks. Solid and dashed line indicate sample 1 and two respectively. Dots mark output power and triangles mark efficiency.

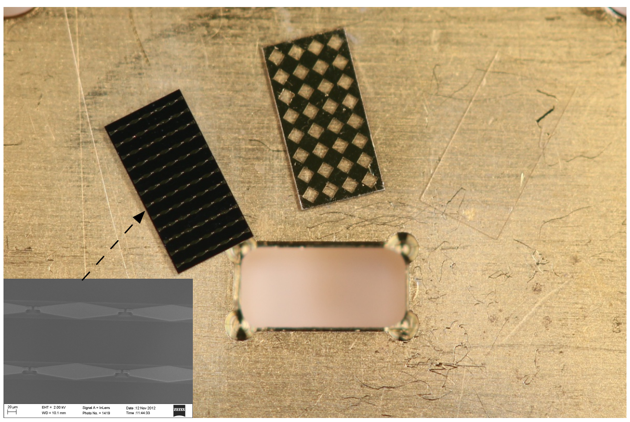

Fig. 6. Photo showing, from left to right, the HBV-array, output bandpass filter and the quartz matching slab. The WR-10 waveguide mounting pocket where the three pieces are stacked is visible in the lower part of the picture. Insert shows SEM picture of 4 unit cells.

IV. Discussion

In the experiments conducted the limited pump power available from the power amplifier meant that the full capabilities of the array could not be explored. Thermal simulations predict that the current array should be able to handle at least twice the input power used. The main thermal issue is heat transport from the mesa to the substrate, limited by the InGaAs epi-layers. Although the devices are not driven to breakdown the internal heating does have an effect on the conversion efficiency, an aspect not included in the predicted conversion efficiency of 5 %. Another non-modeled effect that may contribute to the lowered efficiency is diode yield, which on the tested chip is approx. 70 %. The robustness against single device failure, termed graceful degradation, is an other advantage of using arrays since single device failures have a limited effect on the overall performance [19]. In the array tested here however a loss as large as 3 dB could be attributed to broken devices.

All multiplier arrays presented to date have used uniform arrays and are thus suffering from unequal diode drive levels, except the far-field excited arrays where instead spillover losses limit the applicability of the device. The consequence of this is that the conversion efficiency will vary across the array which in turn leads to a transformation of the output mode. The effects of this was analyzed in [7] and some non-uniform array layouts where proposed to improve the overall array performance. Tailoring the array layout and diode density is likely the next step towards higher efficiency and output power.

Although it could be argued that there exist conventional frequency triplers with higher output power around 250 GHz e.g. [20], due to their higher conversion efficiency, these technologies are more mature and offers less room for a significant increase in output power. Increasing the output power an order of magnitude would call for a significantly more complicated circuit design, and probably also reduced conversion efficiency.

The physical size of the module is comparatively small taking into account the number of power combined varactors and the expected power handling capability. To further reduce the size the linear taper could be replaced by a shorter more narrow-band stepped taper machined in similar fashion as the other two shims. The potential of the project is to achieve 10 % conversion efficiency with several watt input power at W-band.

V. Conclusion

Measurement results for the first waveguide-embedded quasi-optical multiplier array operating above 100 GHz have been presented. The multiplier array is housed in a mechanically compact and for the operating frequency simple shim system, offering an approach that is scalable both in terms of output power and operating frequency.

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