High Power Heterostructure Barrier Varactor Quintupler Sources for G-Band Operation

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***Abstract*— We have designed a frequency multiplier based on Heterostructure Barrier Varactors (HBVs) at 202 GHz. The InGaAs/InAlAs/InP HBV diodes were flip-chip mounted onto an aluminium-nitride (AlN) substrate with the microstrip pattern. The AlN-circuit was then mounted in an ultra compact 30x9 mm waveguide block. A quintupler (x5) operating at 202 GHz produced an output power of 23 mW.**

I. Introduction

The mm-wave and THz frequency spectra is rich on possible applications. But the difficulty to supply room-temperature, compact, high power sources at these frequencies has hampered an otherwise booming technology development. As an example, imaging applications such as a heterodyne receiver array requires local oscillator power of several tens of mW's.

The THz spectral window (~ 0.1-3 THz) , also nicknamed 'THz-gap', is difficult to reach from the electrical side. This is exemplified by the sharp decline of efficiency at higher frequencies for fundamental sources such as IMPATT and Gunn oscillators [1]. Other methods to produce THz output power such as the quantum cascade laser (QCL) is promising but is yet to operate at frequencies well below < 1.4 THz [2].

Because of the inherent difficulty to generate power at these frequencies, the output power from a lower frequency source can be multiplied [3-5] to higher frequencies using a nonlinear device such as the Heterostructure Barrier Varactor (HBV) diode [6]. The HBV has a symmetric capacitance-voltage (C-V) characteristic, operates unbiased and only generates odd harmonics of the pump signal. These specific properties simplify the design of high order multipliers (×3, ×5, ×7, etc.) [7-8]. Moreover, since cascading the epitaxial growth scales the voltage handling capability of the HBV, this device is well suited for high power generation [9-10].

The progress on HBV multiplier includes multi diode quasi-optical circuits [11-12], NLTLs [13] and highly efficient single diode waveguide circuits [14]. For instance, an HBV quintupler (×5) with a state-of-the-art conversion efficiency of 11% has been demonstrated at 100 GHz [15-16], HBV triplers (×3) have been shown to provide 0.2 W at 113 GHz [9], 10 mW and at least 10% efficiency has been demonstrated at short millimeter wavelengths [17-19], and 1 mW has been reported for a HBV tripler up to 450 GHz [20]. In terms of output power, the best results have been achieved using a filter circuit on AlN instead of quartz due to a better heat sink for the flip-chip mounted diode.

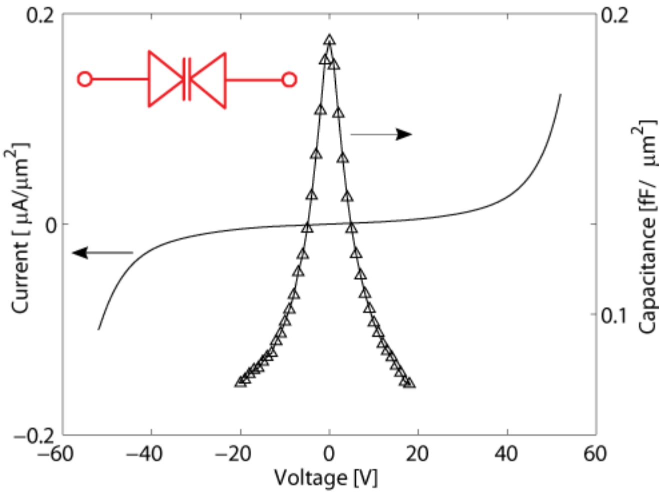

Fig. 1 Graph showing the I-V and C-V curves measured on a 12-barrier 700 μm² HBV. The inset shows the circuit symbol of the HBV as two anti-serially connected diodes.

In this paper we present the design, fabrication and measurement results of state-of-the-art G-band (140-220 GHz) HBV quintuplers. Initially, a brief description of the underlying HBV multiplier technology is presented together with an account of the design and fabrication process. The measurement setup and the results at 202 GHz follow with concluding remarks.

II. HBV Multiplication

The physical property for achieving unbiased multiplication (i.e creation of higher harmonics) in this work is the nonlinearity provided by the HBV diode. This type of diode is realized by epitaxially growing a heterostructure sequence of low-high-low bandgap material. When a voltage is applied across such a semiconductor material, the high bandgap material acts as a barrier for the carriers causing accumulation and depletion of carriers in the respective low bandgap layers. This has the effect of changing the capacitance as a function of the applied voltage C = C(V) as shown in figure 1.

The HBV heterostructure epi-material within this work consists of periodically stacked InAlAs/InGaAs/InP layers[21] repeated three times, in order to withstand high voltages and therefore operate at high power. For this structure, the modulation layer is 250 nm with a doping concentration of 1×10^{17} cm^{-3} and a 13-nm barrier thickness. The epitaxial material was grown by molecular beam epitaxy (EPI930) at the Chalmers Nanofabrication Laboratory.

We chose the symmetric planar topology [9] for the HBV diode. This discrete device is shown in figure 2. It actually consists of four mesas of the aforementioned epi-material that are series connected. This amounts to a total of 12 barriers in series. As shown in figure 1 by the I-V curve, this type of 12 barrier device can operate at voltage amplitudes in excess of 50 V.

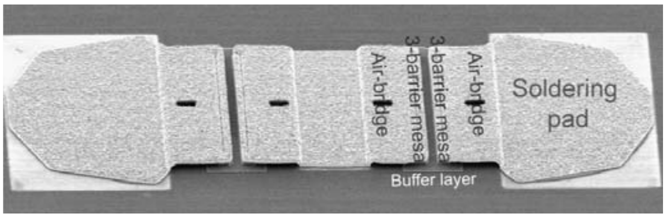

Fig. 2 SEM micrograph of a 500 μm^2 HBV. This 4-mesa device has a total of 12-barriers.

Standard III–V processing techniques were used to fabricate the HBV devices. These techniques include photolithography, e-beam contact evaporation, plasma-enhanced chemical vapor deposition (PECVD), inductively coupled plasma (ICP) dry etching.

III. QUINTUPLER CIRCUIT DESIGN

In order to facilitate efficient multiplication the HBV has to be properly matched at the input frequency and higher harmonics. This was realized using a microstrip circuit incorporating filters and impedance matching elements embedding the diode. The microstrip circuit was fabricated on an AlN substrate (thermal conductivity ~ 170 W/mK) to improve the power handling capability. No DC connection between the waveguide block and the circuit was used since simplicity was one of the design objectives. This also means that open waveguide probes were used both at the input and at the output side. Figure 3 shows the CAD layout for the 3-D electromagnetic solver used to design the quintupler microstrip circuit and waveguide. We can see that the input/output waveguides are connected by probes at each end of the circuit .

The optimum embedding impedances were extracted from harmonic balance simulations using the Chalmers HBV device model [22]. This model self-consistently calculates the interdependent electrical and thermal properties of the device. Three-dimensional FEM modeling was applied to calculate the thermal resistance and electrical series resistance used in the model.

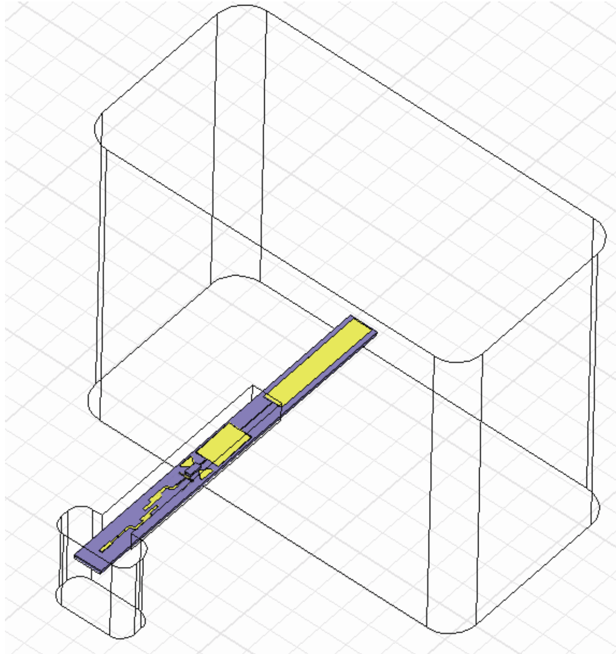

Fig. 3 CAD layout of the quintupler microstrip circuit and waveguide attachments for a G-band quintupler. A 3-D electromagnetic solver was used for the detailed design.

The diced HBV devices from figure 2 were flip-chip soldered onto the microstrip. This hybrid circuit was then mounted in the waveguide block with a WR22/WR5 input and output, respectively. The two-piece compact waveguide block, with dimensions Ø 30 mm × 9 mm, was milled out of brass and gold electroplated. Figure 4 shows a photograph of the two waveguide block halves with the AlN microstrip circuit mounted in the left. The waveguide block has no movable tuners.

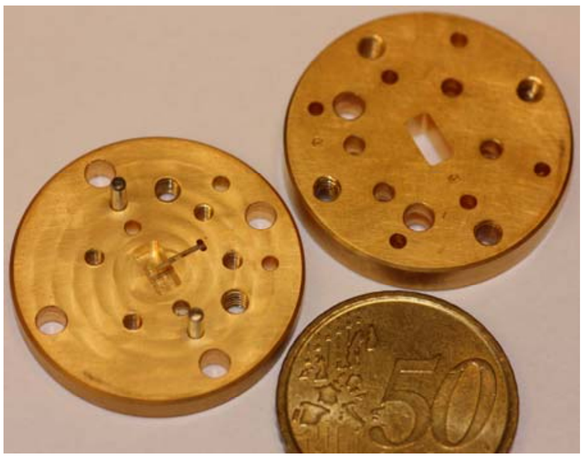

Fig. 4 Two-piece waveguide block halves for the 202 GHz quintupler. The AlN microstrip circuit is mounted in the waveguide channel of the block half on the left. A 50€ cent is included for size comparison.

IV. RESULTS

The input signal to the multiplier was provided by a HP83650B frequency synthesizer followed by a Spacek power amplifier. A waveguide isolator was used between the power amplifier and the HBV multiplier (DUT). The output power was measured using an Erickson PM2 power meter. In figure 5 the output power is plotted as a function of input power showing a maximum output power of more than 20 mW for the 202 GHz quintupler. This result was achieved with a 500 µm^2 HBV diode from the same batch as used for the high power W-band tripler in [9]. The test was limited by available input (pump) power at 40 GHz and even higher efficiency and output is expected at higher input power levels.

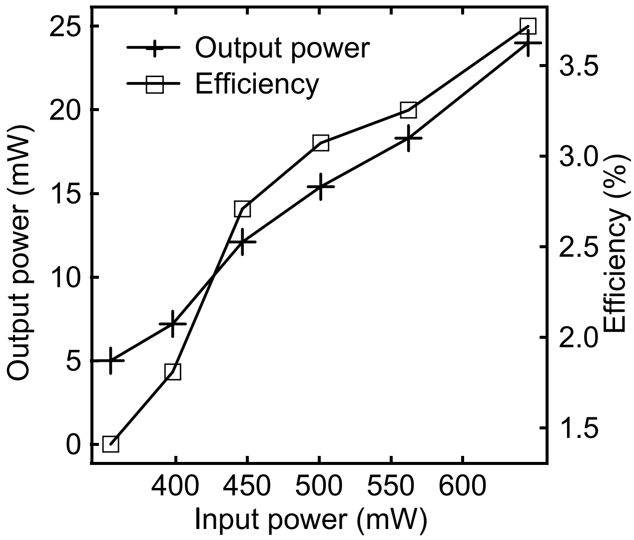

Fig. 5 Graph showing the quintupler output power and efficiency at 202 GHz versus the input power

Figure 6 shows a frequency sweep at a constant input power of 560 mW into the quintupler.

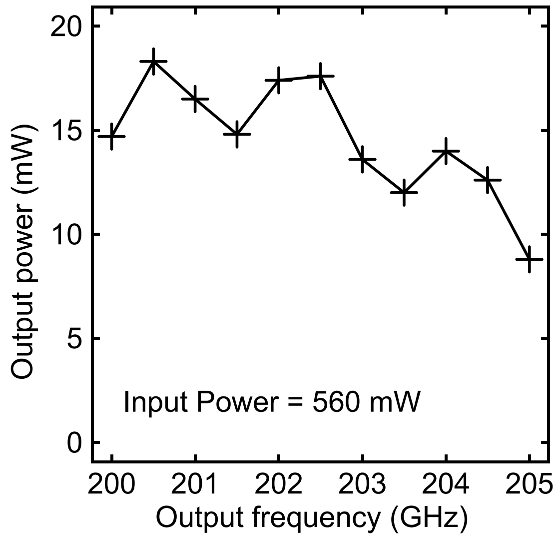

Fig. 6 Graph showing the quintupler output power versus frequency at a fixed input power of 560 mW.

The output spectrum was measured with a Fourier Transform Spectrometer (FTS), which confirmed that the output signal only contains the fifth harmonic.

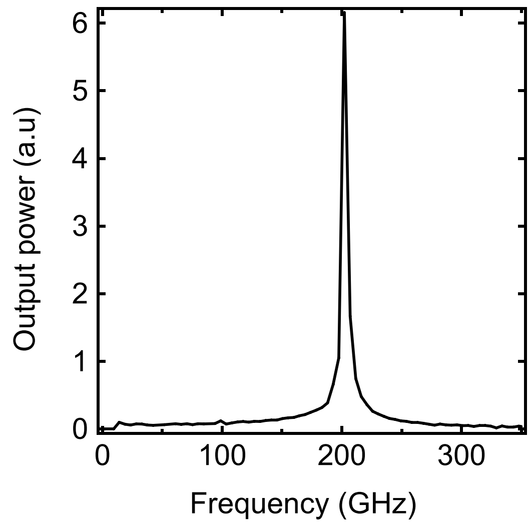

Fig. 7 FTS spectra confirming that the output power measured is all contained in the fifth harmonic at 202 GHz.

CONCLUSIONS

World-record output power performance of more than 20 mW at 202 GHz for an HBV quintupler has been demonstrated. The output power was limited by the available input power so additional improvements of output power and efficiency is expected with increased pump power.

A new and novel design of the waveguide block has been presented that makes the machining of the block simple and repeatable.

Today, the output power for HBV multipliers are comparable to state-of-the-art Schottky doublers at short millimeter wave frequencies. Finally, the HBV multiplier performance can be further enhanced by optimizing circuits, devices and using monolithic integration techniques (MMICs).

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