A 5 Element 450 GHz HBV Frequency Tripler

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Abstract—**A five-element frequency tripler at 450 GHz in a spatial power dividing/combining circuitry has been investigated. The individual triplers are realized with 4 AlGaAs/GaAs-heterostructure barriers bonded onto a membrane-supported coplanar circuit. Dual-offset reflectors together with dielectric phase gratings are applied to achieve efficient power transfer to/from the active devices. The single-element triplers have a maximum output power of 1.05 mW at 451.8 GHz (efficiency: 1.3 %). The unsaturated 5-element frequency tripler generates a maximum output power of 2.01 mW at 451.5 GHz.**

I. Introduction

Interstellar medium radiates energy mainly in the spectral region of submillimeter-waves. Space-borne observation is advantageous to study objects like galaxies or the composition of planetary atmospheres at submillimeter-waves due to the interference with the terrestrial atmosphere. Such applications are corresponding with a strong need for submillimeter-wave receivers, mixers, and especially tunable high-power sources used as local oscillators for heterodyne submillimeter-wave receivers. Traditional high-power sources in the terahertz region are vacuum-tube oscillators or free-electron lasers.

However, they suffer from their limited lifetime, large size, high-voltage supplies, and small tuning ranges. Solid-state oscillators would be more suitable for the applications mentioned above. Although some solid-state devices are theoretically capable to generate oscillations at submillimeter-wavelengths, they are still unable to generate sufficient power for use as a submillimeter-wave local-oscillator and the power level falls off significantly at higher frequencies.

For that reason, frequency multipliers with Schottky diodes or Heterostructure Barrier Varactors pumped by a low-frequency tunable solid-state source provide an attractive alternative to generate the required terahertz frequencies. Starting at millimeter-wave frequencies, several stages of multipliers are necessary to reach terahertz frequencies. Because of the limited input power-handling capability of a single-element, the achievable output power is low. To overcome this problem, one promising way is to integrate several nonlinear devices on a chip monolithically [1]. Another possibility to increase output power is to combine the signals of several single-element multipliers. However, the combining/splitting efficiency decreases with the number of elements if traditional power combining/ splitting techniques by means of waveguide circuits are applied. Spatial power dividing/combining is, as already demonstrated in [2], a more efficient technique to combine power of single-element devices.

The realized setup of the multi-element multiplier is depicted in Fig. 1. This quasi-optical approach provides high flexibility with respect to design changes e. g. in output power which can be done by changing the number of unit cells. Thus, adaption of the multipliers to a special input or output power can be done very easily.

II. Quasi-optical circuitry

As shown in Fig. 1, the quasi-optical circuit is separated into three building blocks: horn antennas, holograms, and mirrors. Due to reciprocity, spatial power divider and combiner can basically be designed in the same manner. The horn antennas couple the waveguide modes to free space. The holograms convert the radiated fields into pseudo-plane waves which are transformed into Gaussian beams via mirrows. The latter are mostly suitable and applied in quasi-optical systems.

A. Periodic phase gratings

In our setup, the inter-element spacing of the multipliers is restricted to $L = 19.0$ mm. Therefore, grating lobes occur in the radiation pattern. The principle of holography is applied to transfer their power into the main lobe. The holograms consist of periodic phase gratings. Their periodicity is equal to the element spacing. The method can also be interpreted as extension of the fractional Talbot effect

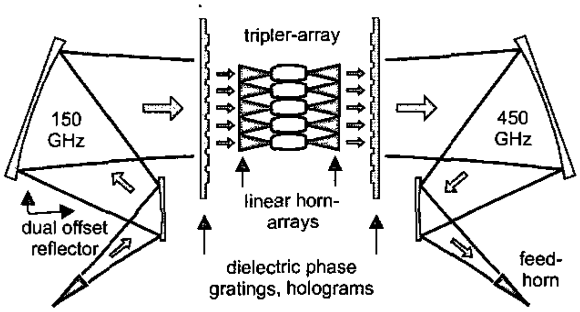

Fig. 1. Structure of the multi-element tripler with quasi-optical feeding.

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[3]. In distances from the antenna array which are fractions of the Talbot length $Z_T = 2L^2/\lambda$, multiple imaging of the periodic field distribution of the horn antenna array occurs. The distance has to be chosen properly to obtain a field distribution with negligible ripple in amplitude. The remaining periodic phase distribution is compensated by the grating to achieve the desired pseudo-plane wave. At 150 GHz, the hologram consists of a simple rectangular groove shape which has an efficiency of 92.5 %. The efficiency is defined as the ratio of the sum of input powers at the multipliers to the feedhorn input power. In principle, the shape of the 450 GHz phase grating can be derived from the 150 GHz design, by scaling the length of the horn antennas and the distance of the grating by the Talbot length Z_T. Since the frequency is tripled and the element spacing L remains constant, Z_T and these dimensions also triple. This would lead to unacceptable ohmic losses in the horn antennas, since their length to wavelength ratio would increase by a factor of 9. Therefore, the hologram has to be redesigned to match to shorter horn antennas. The resulting grating has a triple-stepped periodic surface [3]. The calculated efficiency amounts to 90.7 %.

B. Mirrors: Dual offset reflectors

The mirrors are arranged to form a dual offset reflector. The surfaces have to be shaped to transform the pseudo-plane wave into a Gaussian beam. The design of the dual offset reflector is performed as follows [4]: In a first step, the mirror surface profiles are iteratively fitted by 3-D geometrical optics (GO) by mapping the integral power distributions of the Gaussian beam on the subreflector to those of the expected pseudo-plane wave on the main reflector. This concept and the resulting profile are visualized in Fig. 2. In order to achieve a smooth surface relief, the profiles of the initial design are mapped to parabolic surfaces with modulation by series of sinusoidal functions. The resulting parameters (foci as well as amplitude, phase and length of the sinusoidal functions) are reoptimized by Fourier optics and *local* GO [3]. To our knowledge, the latter is a novel method which takes advantage of both the accuracy of the Fourier optics and the simplicity of the GO. The final design is evaluated by 3-D PO, which confirms the design and our method.

C. Performance

Comparison of calculated and measured performance of the entire 150 GHz quasi-optical input network is summarized in Table I. The 450 GHz output network shows a similar behavior. Its combining efficiency is calculated to 84.98 %.

III. Frequency Triplers

Frequency triplers based on Heterostructure Barrier Varactors (HBV) for power generation in the millimeter-wave region have been extensively investigated during the last decade. The even C/V-characteristic and odd I/V-characteristic of HBVs allow only the generation of odd harmonics avoiding both idler circuits at even harmonics and DC bias. High performance HBV in planar configurations on semi-insulating substrates working in the range of 100-350 GHz have been reported recently. The HBV-group from the Chalmers University, Göteburg, Sweden, started in 1993 with 2 mW at 250 GHz [5], the best results of the following years are: 3.6 mW at 234 GHz, 4 mW at 246 GHz, 11.5 mW at 141 GHz, and 7.1 mW at 221 GHz [6-9]. The HBV-group at the University of Lille, France, reach 5 mW at 216 GHz, 9.55 mW at 247.5 GHz, and 5.7 mW at 289.2 GHz [10-12]. These results represent state-of-the-art of HBV frequency tripling.

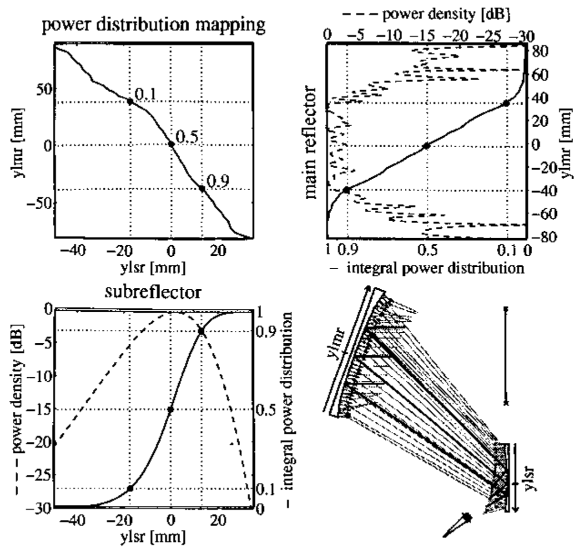

Fig. 2. Concept for the initial GO design.

A. Heterostructure Barrier Varactor

The $Al_{0.7}Ga_{0.3}As/GaAs$ HBV structure is grown by molecular beam epitaxy on semi-insulating GaAs substrate. Fig. 3 shows a SEM image of the fabricated chip after dicing, and Fig. 4 depicts capacitance and current versus

TABLE I
PERFORMANCE OF THE QUASI-OPTICAL INPUT NETWORK WITH DUAL OFFSET REFLECTOR.

Port	Input power [%] calc.	Input power [%] meas.	Phase [degree] calc.	Phase [degree] meas.
A	15.3	11.0	0.9	4.5
B	18.3	17.4	3.0	1.4
C	17.9	17.9	0.	0.
D	18.2	18.1	1.7	-13.1
E	17.1	11.3	-2.9	-3.8
$\sum$	86.8	75.7		

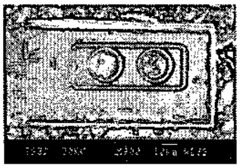

Fig. 3. SEM image of the HBV after dicing.

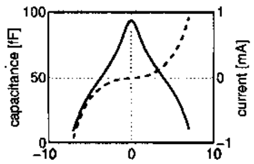

Fig. 4. Capacitance and current versus voltage of the HBV.

voltage. The device dimensions are 50x80μm^2 with a thickness of 80μm. The semi-insulating substrate on the back provides mechanical device stability and simplifies the handling of the flip-chip bonding process.

B. Single tripler performance

The theoretical analysis of the RF-characteristic of the nonlinear device was performed mainly using a set of equations from [13]. As a result, the diode should provide an output power of approx. 2.2 mW at 450 GHz (efficiency: 3.3 %). For this operating point, the passive circuitry has to be matched to an input impedance of $Z_{in} = (13 + j46)\,\Omega$ and to an output impedance of $Z_{out} = (23 + j17)\,\Omega$. The CPW structure of the tripler circuit is supported by a thin membrane. A 1μm gold layer is structured by standard photolithography techniques and electroplated to establish the CPW. The dielectric membrane consists of a silicon-organic compound deposited from hexamethyldisilazane (HMDSN) by plasma polymerisation. The membrane thickness is approx. 4μm. To realize the freestanding HMDSN-membrane, the underlying silicon is removed by KOH-etching. The complete fabrication process of the membrane-based circuit is described in [14]. The tripler chip shown in Fig. 5 can be divided into five building blocks: A rectangular waveguide-to-CPW transition (the waveguide is shorted by a tunable backshort in a distance of $\lambda/4$ from the probe) transforms the waveguide mode into CPW-mode. The transition is followed by a band-stop filter at 450 GHz. To enforce equal potential on the ground planes on both sides of the stubs, air bridges are applied. The HBV is inserted into the circuit by thermo-compression bonding. It should be mentioned, that the bonding process is the last assembly step and is performed on a freestanding 4μm membrane. A band-stop filter at 150 GHz (band-pass filter at 450 GHz) rejects the input signal. At the output, the signal is guided to the output rectangular waveguide by a transition. The chip is characterized in a mill-cut brass fixture and is driven by a 150 GHz Clinotron tube. The tripler output-signal is measured by a Thomas Keating power meter. The single-tripler measurement results are: The maximum output power is 1.05 mW at 451.8 GHz (efficiency: 1.3 %), the maximum flange to flange efficiency is 1.45 %. These are the first results reported for HBV triplers operating in this frequency range.

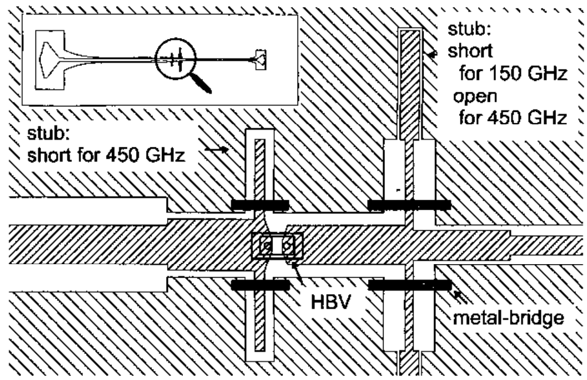

Fig. 5. Tripler chip.

IV. SYSTEM PERFORMANCE

The quasi-optical multiplier has been set up with dual offset reflectors at the input and output as described above. Two different measurement setups are investigated: In the first setup, the sensor of the quasi-optical power meter is located at the beam waist position of the feedhorn. This position is located slightly behind the horn aperture of the 450 GHz-feedhorn (Fig. 1). The second configuration is depicted in Fig. 1. The RF power at 450 GHz is collected by this gaussian-beam-horn (feedhorn). Nevertheless, for power detection the signal is again coupled into free space and focused on the sensor of the quasi-optical power meter. It has to be mentioned that the multiplier output power is not yet saturated by the available fundamental oscillator power level of about 300 mW.

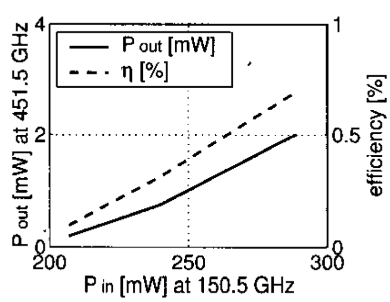

Fig. 6. Power sweep without feedhorn at the 450 GHz side.

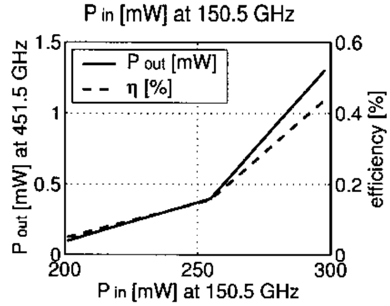

Fig. 7. Power sweep with feedhorn at the 450 GHz side.

A. Measurements

The output power at 450 GHz was measured by a Thomas Keating power meter. Fig. 6 and Fig. 7 show preliminary measurements which are in good agreement with the estimated values derived from single tripler measurements. The maximum output power is 2.01 mW with an efficiency of 0.7 %. When coupling the output power into a feedhorn, the maximum output power decreases to 1.31 mW with an efficiency of 0.44 %. We expect an output power of about 4 mW with adequate input power at 150 GHz.

B. (Graceful) degradation

Many applications require the use of power combining networks to achieve a power level from solid state devices which is many times higher than available from a single device. In such case, it is always important to estimate the effect of failures of single elements on the overall system performance. In case of failure, it is preferable to have graceful degradation. This means that the operating multipliers are not affected by the failures and their output power is coupled to the output port as before. In this special assembly, all divider output ports and combiner input ports are isolated from each other because of the high directivity of the used horn antennas. Considering an N-multiplier system in which m elements fail (M=N-m elements remain under operation), without feedhorn the output power will decrease to M/N of its original value [3].

This can be tested by switching off individual multipliers by filling the corresponding input horn with absorbent material. Fig. 8 (a) shows the M/N decrease of output power versus the number of failed elements. By coupling the output power into a feedhorn as depicted in Fig. 1, this behavior gets lost. Fig. 8 (b) gives a picture of the $(M/N)^2$ decrease for that case according to the theory [16]. Thus, if two multipliers fail, the input power of the combiner decreases to 3/5 of the original value. The output power, however, drops to nearly one third.

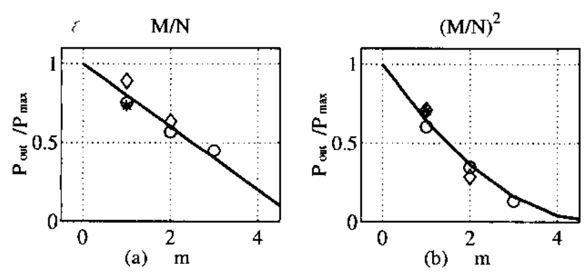

Fig. 8. Decrease of the output power of the combiner without (a) feedhorn and with feedhorn (b) versus m failed multipliers.

V. Conclusion

The single-element tripler has a maximum output power of 1.05 mW at 451.8 GHz (efficiency: 1.3 %). The unsaturated 5-element tripler generates a maximum output power of 2.01 mW at 451.5 GHz. Till now, the highest published

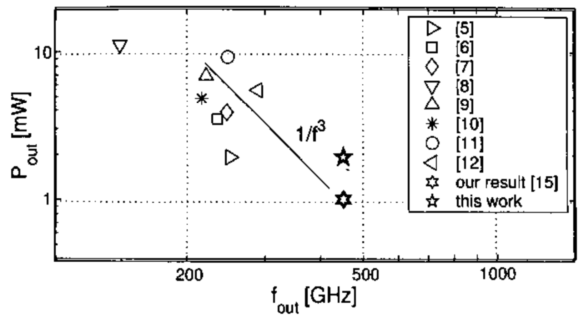

Fig. 9. Comparison of state-of-the-art HBV triplers.

HBV output frequency was about 350 GHz (comp. Fig. 9). Our results at 451.8 GHz [15] represent the highest output frequency of HBV tripling. The output power is state-of-the-art as well, under the assumption of a $1/f^3$ decrease which is a common assumption in this frequency region. The 5-element-tripler doubles the output power, and 4 mW we expect with the saturated multi-element-multiplier. Future work will include a 10-element-tripler and a 8-element-doubler.

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