A Multi-Element 150/300 GHz Spatial Power Dividing/Combining Frequency Doubler

Bert Schumann, Michael Höft, and Rolf Judaschke

Arbeitsbereich Hochfrequenztechnik, Technische Universität Hamburg-Harburg, D-21071 Hamburg

***Abstract* — A five-element frequency doubler at 300 GHz in a quasi-optical spatial power dividing/combining circuitry has been investigated. The individual frequency doublers are realized with GaAs-Schottky-diodes in waveguide technique with 4 % efficiency. Holography is applied to achieve efficient power transfer to/from the active devices. Preliminary measurements are in good agreement with the expected system performance.**

I. INTRODUCTION

There is a need for millimeter and submillimeter-wave solid-state sources for local oscillators in heterodyne receiver systems. Usually, sources in the submillimeter-wave range are realized by means of an oscillator (Gunn or IMPATT), followed by a multiplier-chain to reach the desired frequency. Typical applications are radio astronomy or atmospheric sensing. Increasing the output power would enable several other applications, especially active systems like radars. One possibility to increase the available power in the higher millimeter- and in the submillimeter-wave range is to combine the signal of several multipliers [1]. Spatial power dividing/combining is a promising technique for efficient power generation at millimeter-wave frequencies. The realized setup of the multi-element multiplier is depicted in Fig. 1. It can be divided in three main blocks: A quasi-optical power dividing circuit, a linear array of identical frequency multipliers, and a quasi-optical combining network.

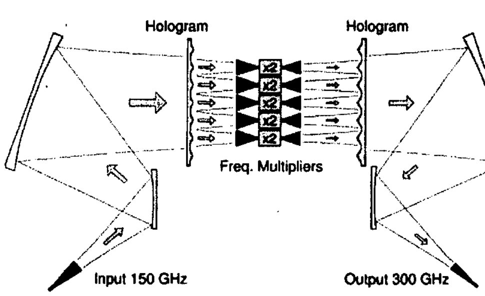

Fig. 1. Multi-element frequency doubler

II. QUASI OPTICAL CIRCUITRY

The quasi-optical multi-element networks can be separated into three parts: horn antennas, holograms, and feed systems [1]. The horn antennas are used to couple waveguide modes to free space. The holograms couple the radiated fields to pseudo-plane waves. The pseudo-plane wave of the 300 GHz output signal has to be transformed into a Gaussian beam since those beams are most suited and applied in quasi-optical systems [2]. The Gaussian beam of the 150 GHz input feed on the other hand has to be transformed to a pseudo-plane wave.

A. Holographic power splitting/combining

Since the inter-element spacing of the frequency doublers cannot be decreased to – in our case - less than 19.0 mm due to their housing geometry, grating lobes occur in the radiation pattern. Holography is applied to transfer their power to the main lobe [3]. The holograms consist of dielectric surface-relief gratings with a periodicity of 19.0 mm.

Two Teflon holograms are used: The 150 GHz hologram has a simple rectangular groove shape resulting in an efficiency of 92.5 % with a 90 % bandwidth of 5.3 % [4]. The efficiency is defined by the ratio of power transfer to the main lobe in an infinite array setup. Since the number of grating lobes at 300 GHz is twice the number of lobes at 150 GHz, the shape of the 300 GHz hologram has to be more complex: It shows a two-stepped groove shape to reach an efficiency of 92.9 % with a 90 % bandwidth of 4.3 %. Note that the design of the hologram is independent of the number of elements [3]. The number of elements defines the spatial field distribution in front of the hologram. This field distribution has to be generated by the quasi-optical feed system.

B. Feed system

The transformation of the pseudo-plane wave to a Gaussian beam can be performed by phase modulation with a mirror set on the one hand, or a system of dielectric

0-7803-7239-5/02/$10.00 © 2002 IEEE

lenses on the other hand. The required phase profile to be generated by the lenses can be calculated in a straightforward manner in applying the thin lens approximation [2]. The field of the Gaussian beam is calculated in the plane of the first lens while the desired pseudo-plane field produced by the hologram under the excitation of five sources is calculated in the plane of the second lens. The calculations can be performed rigorously with 3-D Fourier optics. By comparing the power distribution in these two planes, the geometrical optics (GO) rays can be calculated in between the lenses. The phase modulations in these two planes are due to the difference between the phase distributions of the GO angle and the calculated fields. The resulting combining efficiency is calculated to 97.5 %.

In a first step, we performed the described field matching scheme by the design of two Fresnel lenses. However, the efficiency was degraded due to the Fresnel steps, losses in the dielectric layers, and undesired surface reflections as described below for a realized 150 GHz feed system.

Therefore, it is more suitable to apply a dual offset reflector setup. The profile of the surfaces has to be shaped appropriately to fulfill the phase modulations. The design for the linear array of five elements is based on a single offset reflector with parabolic torus shape [5]. In a GO point of view, the resulting beam is comparable to the radiation pattern of a finite line source with uniform phase distribution. Since the pseudo-plane wave is only needed in one dimension, this results is an initial surface for the main reflector of the dual offset reflector design. The sub-reflector has to be positioned in parallel to the linear array as already sketched in Fig. 1. The surfaces of the reflectors are modulated with four sinusoidal functions of different amplitude, phase, and length. The optimization of their values has been performed by 2-D physical optics (PO) calculations. The resulting calculated coupling efficiency is 90.3 % for the 150 GHz feed system, and 90.5 % for the corresponding system at 300 GHz.

C. Measurements

The performance of the quasi-optical setups has been verified at 150 GHz. The characterization of the 150 GHz hologram has already been reported in [4]. Measurements have been performed in a plane in front of the hologram with a vector field measurement system [6]. The comparison between measurements and calculated fields shows excellent agreement (deviations being less than 1 %).

In the same manner, measurements have been carried out with the dual offset reflector as feed system. The system is driven by a stabilized 150 GHz source. The input feed consists of a dual-mode horn to support the Gaussian beam. Again, vector field scans have been performed in a plane in front of the hologram. Fig. 2 shows a comparison of measurements and corresponding 3-D PO calculations of magnitude and phase of the electric field. It is obvious that the dual offset reflector converts the Gaussian beam field distribution to the desired one of the finite linear multiplier array. The agreement between measurements and calculations can be characterized by computation of their coupling factor, resulting in 94%. Nevertheless, the setup was discarded since it suffers from an error in the y-axis-design. Currently we are working at a redesign.

Therefore, the performance of the overall input network

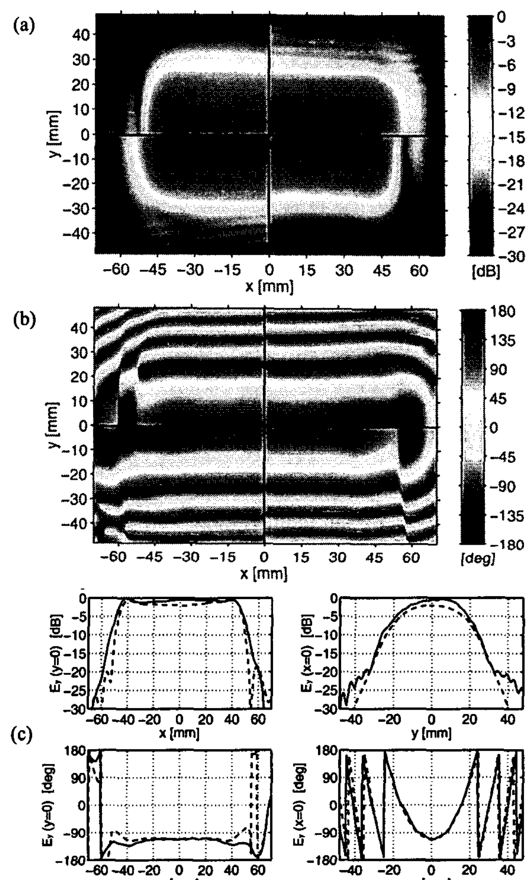

Fig. 2. Comparison of the electric field of the dual offset reflector. (a) Magnitude and (b) phase: Meas. ($x\cdot y > 0$) and calc. ($x\cdot y < 0$). (c) Cuts in $x = 0$ and $y = 0$: Meas. (—), calc. (---).

was characterized with Fresnel lenses as feed system. As mentioned above, this design suffers from losses. As a result, only 58.5 % of the input power couples to the frequency doubler ports. The input power distribution of the multiplier array is shown in Table I. The theoretical values have been calculated neglecting any losses according to the assumption of ideal thin lenses. Furthermore, the phase distribution is listed in the table.

TABLE I
PERFORMANCE OF THE QUASI-OPTICAL INPUT NETWORK WITH FRESNEL LENSES

	Percent of input power		Phase in degree	
Port	calc.	meas.	calc.	meas.
A	20.0	10.7	4.1	8.7
B	19.2	13.9	0.7	12.8
C	19.4	10.8	0	0
D	19.2	12.1	0.7	3.9
E	20.0	11.0	4.1	22.0

III. FREQUENCY DOUBLER

The whisker-contacted Schottky-Diode frequency doubler (150/300 GHz) is an improved version of a standard crossed-waveguide design, previously reported [7]. This design uses a coaxial choke to couple power from the input to the output waveguide. Two conducting backshorts in the D-band input and J-band output waveguide perform tuning to match the diode impedance to the circuit. The backshorts are adjusted by means of a micrometer-type driving mechanism. The GaAs-Schottky-diode is conventionally soldered on top of the choke. The anode is contacted with an electro-chemically formed whisker-tip, made from a 25 µm gold-nickel alloy (Au82/Ni18) wire.

The diodes were delivered by the Technical University of Darmstadt, Germany. The type WV1211 has a junction capacitance of 12 fF, a breakdown voltage of 11 V, and a DC series resistance of approximately 11 Ω. The epitaxial layer has a thickness of 500 nm and is doped with a concentration of $10^{17}\,cm^{-1}$. The honeycomb Schottky contact area (Pt) with a diode diameter of 5 µm is SiON passivated (600 nm). The diode-chip has a substrate thickness of about 60 µm.

The optimum diode impedances at both fundamental and harmonic frequency are calculated according to [8], where an accurate model of the Schottky diode has been developed. The frequency multiplier is analyzed by barrier charge parameterization for operation in the varactor (i.e. purely reactive) mode. From this analysis, optimum diode impedances are calculated. The embedding impedance of the circuit is optimized to the diode impedance by the commercial finite element simulator HFSS from Agilent Technologies.

A linear array arrangement of frequency doublers requires a modified general multiplier setup: The input and output waveguides have to be in-line (not crossed), and the doubler width has to be reduced according to small inter-element spacing. Fig. 3 depicts the modified structure with both input and output rectangular horn antennas. These antennas fulfill the quasi-optical demands of the dividing/combining circuit. All tuning elements and input/output ports are placed in one plane, according to the linear array setup. For a 2-D-setup, the backshort- and whiskerpost-micrometer drives have to be removed. The multiplier width is 19.0 mm, fitting to the flange UG-387/U-M. The height is about 25.8 mm (without tuning drives).

This multiplier was developed within the framework of the research group "Submillimeterwellen-Schaltungs-technologie" funded by the Deutsche Forschungs-gemeinschaft DFG. A clinotron tube (460 mW output power at 150 GHz [9]) has been used as input source to pump the multiplier array. In future, the multi-element-multiplier will be pumped by a multi-element-oscillator at 150 GHz.

A. Single doubler performance

The maximum doubler efficiency was measured to be 5.73 % at 300 GHz (beyond 300 GHz it was slightly larger [7]). The maximum output power is 4.26 mW. Fig. 4 shows typical results. All five multipliers of the linear array were adjusted to approx. 4% efficiency.

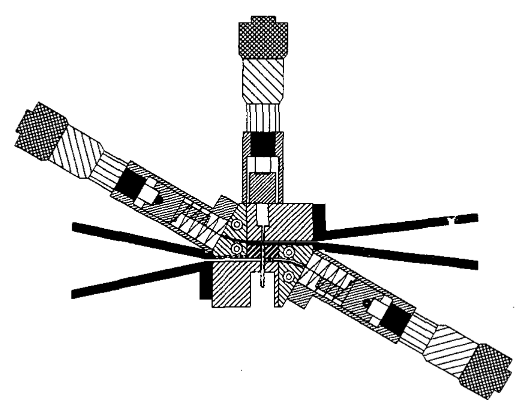

Fig. 3. Cross-section of the in-line multiplier

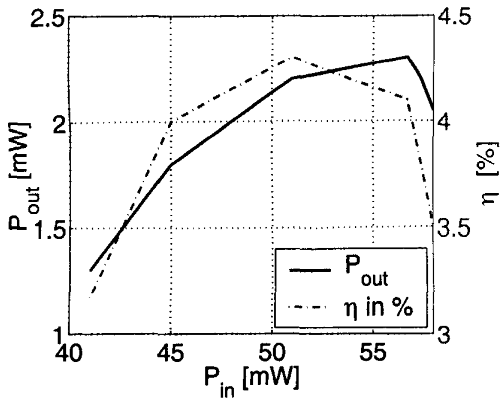

Fig. 4. Typical performance of a single frequency doubler

IV. System Performance

The quasi-optical multiplier has been set up with Fresnel lenses at the input and dual offset reflector at the output as described above. The output power at 300 GHz was measured by a Thomas Keating power meter.

A preliminary measurement result of the system is an output power of 8.35 mW (efficiency of 1.82 %) when driven with an input power of approx. 458 mW. After the redesign of the feed system, we expect an overall efficiency of 2.56 % resulting in 11.5 mW at 300 GHz which is state of the art [10].

Acknowledgement

The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for financial support.

References

[1] K. Schünemann, R. Judaschke, M. Shahabadi: "New Quasi-Optical Circuit Technology for the Submillimeter-Wave Range," *The 30th ESLAB Symposium on Submillimeter and Far-Infrared Space Instrumentation*, Netherlands, 1996.

[2] P.F. Goldsmith, *Quasioptical Systems - Gaussian Beam Quasioptical Propagation and Applications*, New York: IEEE Press/Chapman & Hall Publishers, 1997.

[3] M. Shahabadi, K. Schünemann, "Millimeter-wave holographic power splitting/combining", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-45, pp. 2316-2323, Dec. 1997.

[4] M. Höft, J. Weinzierl, R. Judaschke, "Broadband analysis of a D-band holographic power combining circuit," *Proc. IEEE MTT-Symp.*, Phoenix, USA, pp. 1407-1410, May 2001.

[5] M. Höft, B. Schumann, R. Judaschke, M. Shahabadi, "A 65 GHz holographic power combiner," *Proc. IEEE MTT-Symposium*, Anaheim, USA, pp. 1833-1836, June. 1999.

[6] J. Weinzierl, R. Schulz, H. Brand, L.-P. Schmidt, "A vector field measurement system for 150 GHz," *Proc. 25th Int. Conf. on Infrared and Millimeter Waves*, Beijing, China, pp. 353-354, Sept. 2000.

[7] B. Schumann, and R. Judaschke, "Accurate Analysis and Optimization of Whisker-contacted Schottky-Diode Frequency Doublers," *Proc. 25th Int. Conf. on Infrared and Millimeter Waves*, Peking, China, pp. 349-350, Sept. 2000.

[8] M.T. Faber, J. Chramiec, M.E. Adamski, *Microwave and millimeter-wave diode frequency multipliers*, Artech House, 1995.

[9] K. Schünemann, D. M. Vavriv, "Theory of the Clinotron: A Grating Backward-Wave Oscillator with Inclined Electron Beam," *IEEE Transactions on Electron Devices*, vol. 46, no. 11, pp. 2245-2252, Nov. 1999.

[10] H. Eisele, and G.I. Haddad, "Recent Advances in Two-Terminal Devices for mm-Wave and THz Applications," *24th Workshop on Compound Semiconductors Devices and Integrated Circuits held in Europe*, XII-3-XII-4, 2000.