A 600 GHz Planar Frequency [Multiplier Feed On a Silicon Dielectric-Filled Parabola

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Abstract A novel all-planar quasi-optical schottky varactor diode frequency doubler has been fabricated and has produced more than 1 mW of output power at 600 GHz with an approximately 2 percent conversion efficiency. This simple-to-assemble all-planar diode multiplier could replace complicated waveguide blocks commonly used at submillimeter-wave frequencies to provide local oscillator power for terahertz receiver components.

I. INTRODUCTION

Previously, a simple quad-bridge diode configuration has been proposed for submillimeter-wave frequency multipliers, and the concept was verified by testing a scale model at 20 GHz [1], The circuit shown in Figure 1 ensures inherent isolation between the two input ports and the two output ports allowing us to eliminate complicated filter structures required in single diode frequency multipliers, In addition, the two input ports can be pumped in series by a single source without employing bulky power combining components such as hybrids [2].

Coupling RF power to the device through a waveguide-post [3] has been a popular approach for many submillimeter frequency multipliers. Other MMIC type multipliers accommodate a portion of matching circuit as well as the diodes on the same chip [4]. In most cases, however, these multiplier circuits use at lease, a section of metallic waveguide for input and output power coupling. In our design, we achieve a direct power coupling between free space and the quad-diodes by adopting two pairs of polarization-switched double-slot antennas at the focal point of the dielectric-filled parabola, This s[ot-antenna / dielectric-filled parabola system transfers power without suffering losses due to thick-substrate modes. Furthermore, the double-slot antennas have very high coupling efficiencies to the Gaussian beam incident onto the focal plane of the parabola when the Gaussian beamwaist is about 70 percent of the parabola radius The double-slot antennas deliver to and extract from the quad-diodes the same amount of power with opposite polarity, behaving almost like a ()/ IN) degree hybrid with a small leakage between the two

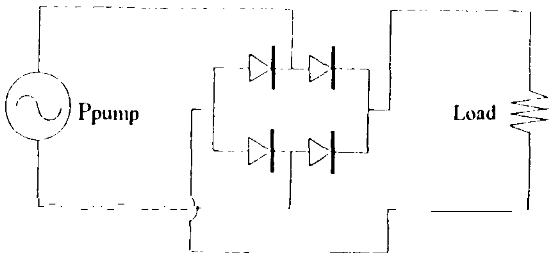

Figure 1. The quad-diode frequency doubler configuration. The input and the output circuits do not require any filters, and can be directly connected to the source and the load without hybrids.

input / output ports that is described by the mutual coupling coefficient between the two antennas. To obtain maximum conversion efficiency. compact coplanar transmission-line matching circuits, designed to transform the antenna impedance into the opt i mum diode de-embedding impedance only at a single frequency, could be placed between the antennas and the diodes,

II. CIRCUIT FABRICATION

A 600 GHz frequency doubler was monolithically fabricated on a 5-mil thick GaAs substrate (Figure 2). The circuit contained four diodes with identical $1x4\,\mu m^2$ anodes on three separate 13s13 μm^2 mesa squares with a 0,22 μm-thick n-layer doping profile of 2.6x10'7/cn13 and a 1 μm-thick buried n^+-layer doped to 5x10' ^{8}/cm^3. The ground planes and the air-bridges. 3 μm-high and 10 μm-wide, tightly shield all four varactor diodes in the $40x40\,\mu m^2$ area at the center of the doubler circuit. The air-bridges arc required to prevent the unwanted slot-line modes as the diodes are connected only to the center conductors of the coplanar waveguide outside of the quad area, Since the effective wavelengths are only 380 μm and 190 μm at 300" GHz and 600 GHz, the equivalent circuit for the $40x40\,\mu m^2$ quad area should include several distributed elements in addition to the intrinsic diode model (Figure 4). The circuit parameters were obtained by fitting S-parameter data to the results from a two-dimensional structure simulator over the frequency range of interest In the equivalent circuit. an S-

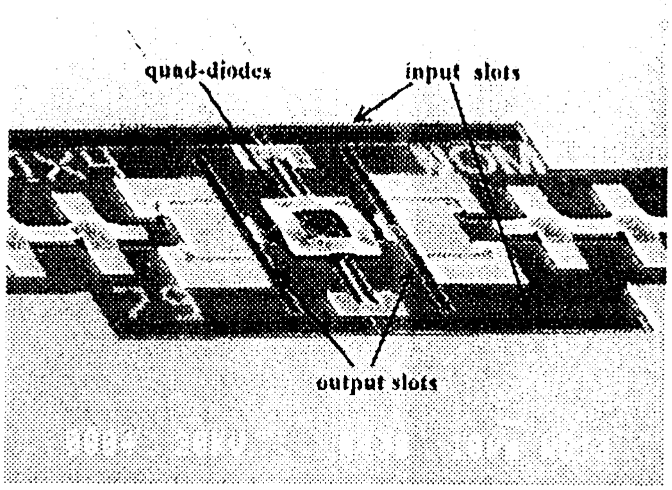

Figure 2. SEM picture of the quasi-optical frequency doubler. A DC bias network extends from the center of the output slot antennas and allows us to estimate the RF input power coupling by monitoring the change to the diode DC bias under pumped conditions.

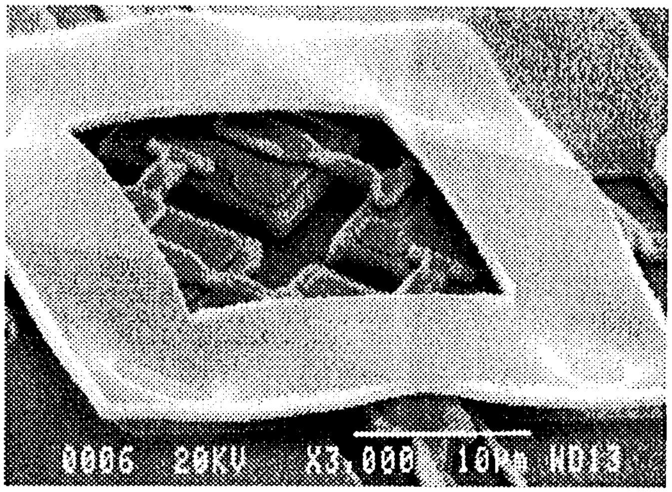

Figure 3. Close up of the quad area in the frequency doubler circuit. The air-bridges, placed 3 μm above the firer diodes and connecting all the ground planes together, suppress slot-line modes on the coplanar transmission lines.

parameter tile that converts CPW mode to modes in three coupled transmission-lines was also used. From a simple diode theory, we calculated the series resistance to be 9.2 Ohms and the zero bias junction capacitance to be 6.8 fF for an individual diode. The HP-MDS harmonic balance simulator predicted the optimum de-embedding impedance for the quad area 10 be 19 + j69 Ohms across the two input terminals at 300 GHz, and 15 + j9 Ohms for the output terminals at 600 GHz when the individual diode is reverse-biased to -1 Volts

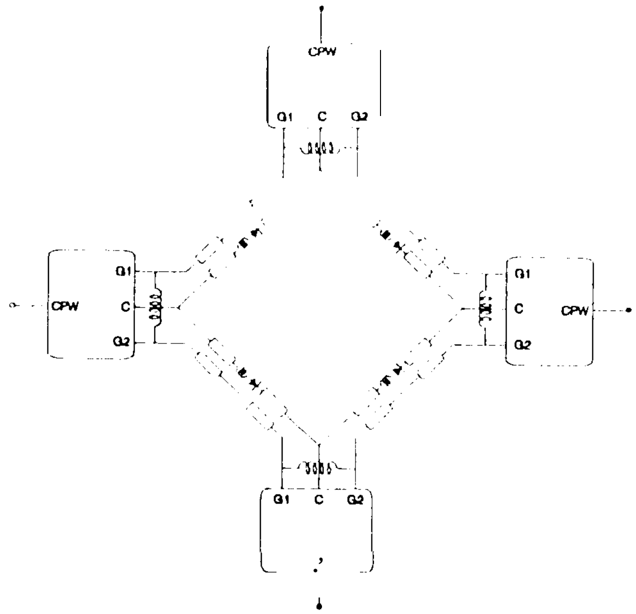

Figure 4. Equivalent circuit for the 40x40 μm^2 quad area in the 600" GHz doubler. Each air-bridge present a small inductance between two ground planes Gaps between the mesa and the ground planes were modeled as transmission-lines. The circuit parameters were obtained by running a 2-D structure simulator with all diodes replaced with electrical shorts.

Two pairs of cross-polarized double-slot antennas surround the quad-diodes for separate input and output power coupling to the free space. The slots were 240 μm-long (approximately half-wavelength) and 140 μm-apart (quarter-wavelength) at the input frequency of 300 GHz and 120 pm-long and 70 pm-apart at the output frequency of 600 GHz. The antenna slot-widths were 10 μm and 5 μm for the input and output respectively. These antenna dimensions were chosen for an equal E and H-plane beam profile, and to obtain the optimum coupling to the Gaussian beam propagating into the silicon parabola, Since the space for matching circuits between the quad area and the slot antennas were limited (45 μm for the input and 12.5 μm for the output), we have only designed and tested two types of lumped clement matching networks until now, In onc circuit, shunt capacitors formed by an extra insulating SiN layer (ε_r=6.7) of 0.12 μm on top of the ground plane were used. and large spiral inductors were used in the other circuit. The capacitor circuit depends on the accurate SiN layer thickness and its dielectric constant and the spiral matching circuit tends to suffer from the conductor and the radiation loss, The calculated impedances from a two-dimensional structure simulators are somewhat deviated from the ideal dc-embedding impedances. However, HP-MDS still predicted 10 dB (capacitor matching) and 12dB (spiral matching) of conversion loss which is dcftncd as the second harmonic power radiated by the output slots divided by the pump power collected by the input slots.

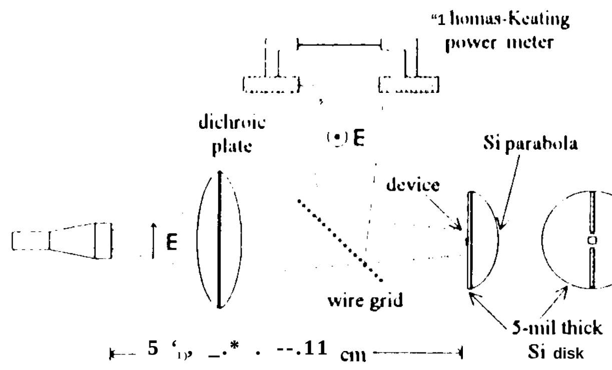

Figure 5. Measurement setup for the 600 GHz doubler.

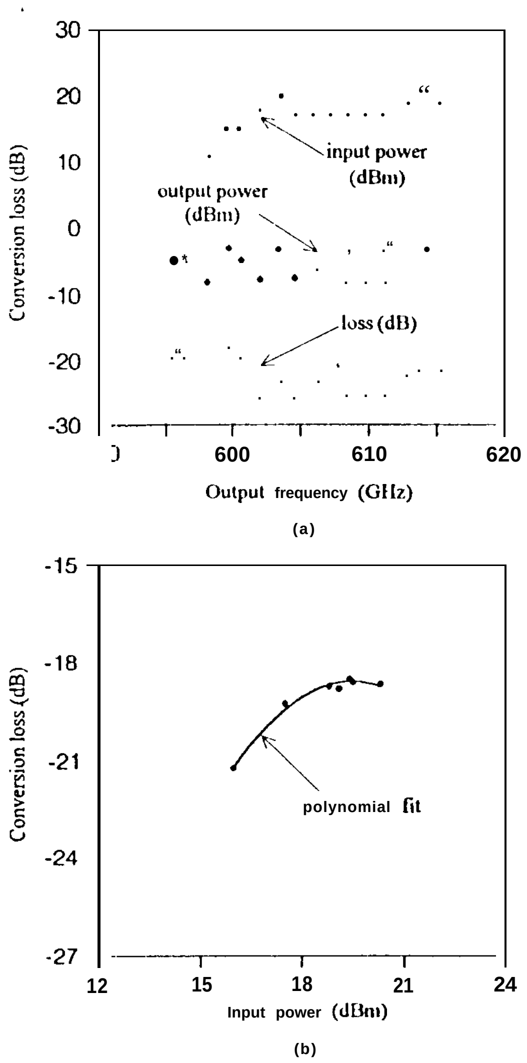

Figure 6. Measured data. (a) Conversion loss vs. output frequency from a spiral matching circuit. and (b) Conversion loss vs. input power level at the output frequency of 614 GHz from a capacitor matching circuit. The measured output power showed peaks at 1 GHz interval due to the resonances in the input path.

The complete doubler circuitry was fabricated on one side of the 600 x 600 μm² chip which was first mounted at the center of a 5-mil thick silicon wafer before being placed at the focal point of a silicon parabola, 2 cm in diameter and 5 mm in focal length.

III. MEASUREMENTS

In our experiment, a carcinotron capable of producing more than 100 mW of power between 290 and 310 GHz was used to pump the diodes A corrugated horn with 1.25 mm beamwaist was attached to the cacinotron to produce a vertically polarized Gaussian beam at 300 GHz. A single lens made of Rexolite, placed 5 cm away from the feed horn. was design to focus the input beam to the silicon parabola with 7 mm beamwaist. In between the lens and the parabola, a horizontally polarized wire grid is inserted to reflect the second harmonic signal returning from the parabola into the Thomas-Keating acousto-optic power meter. In order not to collect any scattered pump signal, we added a dichroic plate with 1.5-inch aperture size in front of the power meter. The 30-mil thick metallic plate perforated with 15-mil diameter round holes on a triangular lattice at 18-mil spacing, attenuates 300 GHz signal by more than 40 dB, and transmits 600 GHz signal with less than 1 dB of insertion loss, Throughout the experiment, the power meter was frequently replaced with a 600 GHz schottky diode detector in a waveguide block which cut off the pump signal, and confirmed the presence of the second harmonic signal. To estimate the doubler conversion loss, we replaced the parabola with the power meter, and measured the input power that was collected by the parabola earlier, An absorber with 2 cm hole opening was used to block the part of the beam that was not captured by the parabola. This calibration scheme allowed us to estimate the input path loss but failed to provide any information on the output path loss.

In our current setup, the signal travels more than 34 λ at the input frequency and 68 λ at the output frequency inside the silicon parabola, Such a large parabola size makes the device alignment at the focal point and the dielectric losses in the parabola extremely critical for the input and output power coupling. As an example, we have noticed considerable changes in output power as different 5-mil thick silicon wafers were placed between the device and the silicon parabola. The best output power we have measured so far is 1.4 mW at 612 GHz with 19 dB conversion loss from a shunt capacitor matching circuit, The same circuit also showed 16 dB conversion loss at 596 GHz with smaller input and output power levels However, this circuit produced significant powers only at these two frequencies. On the other hand, the spiral inductor matching circuit showed slightly larger conversion loss but broader frequency bandwidth with output power peaks at about 1 GHz intervals in the measured frequency bandwidth of 594 to 614 GHz (limited by available pump source). In all cases, the DC-bias to the diodes made little difference on the circuit performance and the diodes were left to be self-biased by the pump signal. Since the input coupling, which can be monitored by the bias change, also peaked at 1 GHz output frequency interval, we now believe the main resonance exists in the input path with the corresponding cavity length of 30 cm in air. Up to this point, a number of attempts including placing a quartz matching layer on top of the parabola have been made but not yielded any improvements.

ACKNOWLEDGMENT

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