Design and Performance of a 2.7 THz Waveguide Tripler

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ABSTRACT

The design and performance of a 0.9 THz to 2.7 THz waveguide tripler are presented. An unusual split block configuration with parallel input and output waveguides accommodates a monolithic membrane diode (MoMeD) circuit [1, 2]. Submicron planar GaAs Schottky diodes in single and antiparallel pairs are implemented with matching filters on a 3 μm thick suspended substrate as part of the MoMeD structure. The filters are a combination of short hammerheads [3] and high-low impedance elements. Only a few circuit variations have been measured to date. The best current performance shows an output power of 0.1 μW and an efficiency of 0.002% at the band center frequency of 2.55 THz.

INTRODUCTION

The submillimeter-wave spectral bands from 300 THz to 3 THz are some of the least explored, yet information rich, regions of the electromagnetic spectrum with applications in radio astronomy, planetary science, and Earth remote sensing. To reach the frequency regime above one THz with high resolution, high sensitivity spectral line detectors, local oscillators (LO) sources are desperately needed. For space applications it is essential that such sources be realized with robust, low power consuming, solid-state technology. Likewise the source must be strong enough (1 to 50 μW) to pump superconductor-insulator-superconductor (SIS) mixers or hot-electron-bolometer (HEB) mixers. Recently a 1.2 THz solid-state source with 70 μW output power was demonstrated at JPL using planar Schottky diode multipliers and a power amplifier at W-band [4]. The highest reported LO-frequency generated by a multiplier using planar Schottky diodes is 1.5 THz (a doubler pumped by a far infrared laser). The observed output power was 40 μW [5]. With a traditional whisker contacted frequency tripler, 15 μW at 1.4 THz was obtained [6] using a backward wave oscillator (BWO) at 450 GHz. The advantages of using planar diode multiplier designs instead of whisker-contacted diodes are mechanical robustness, reproducibility, and simplified handling and mounting. These features are of great advantage for space applications.

In this paper we present the design and performance of a 2.7 THz waveguide tripler which was originally intended to be one of the upper stages of a multiplier chain on the Far Infrared and Submillimeter Space Telescope (FIRST/Herschel). Since a solid-state pump source at 850 GHz was not available, we used a far infrared laser as an input source for the measurements reported.

MONOLITHIC MEMBRANE DIODE (MOMED) CIRCUIT

The 0.9 THz to 2.7 THz frequency tripler uses the monolithic membrane diode (MoMeD) fabrication techniques [7] developed for a 2.5 THz Schottky diode mixer [1]. The performance of high frequency circuits suffers dramatically due to substrate losses. In order to keep the circuit losses as low as possible the active and passive high frequency structures are defined on a very thin GaAs membrane, as shown in Figure 1. The dimensions of the membrane are: 3 μm thick, 30 μm wide, and approx. 700 μm long. The membrane is attached to a sturdy 50 μm thick GaAs frame (outer dimensions: 1.5 mm x 1.0 mm) to provide mechanical rigidity and facilitate the handling of the device during fabrication and mounting. The complexity of the multiplier circuit is higher than the mixer circuit [1] because we implemented beam leads on top of the thin membrane (Figure 1b). They provide the connection to ground for the DC bias loop and for the RF. The dimensions of the beam leads (Fig. 1b) are: 1 μm thick, 15 μm long, and 10 μm wide. The complete MoMeD circuit is defined on a MBE grown semi-insulating GaAs wafer with a heavily doped ($5x10^{17}/cm^3$) epitaxial layer of 100 nm thickness.

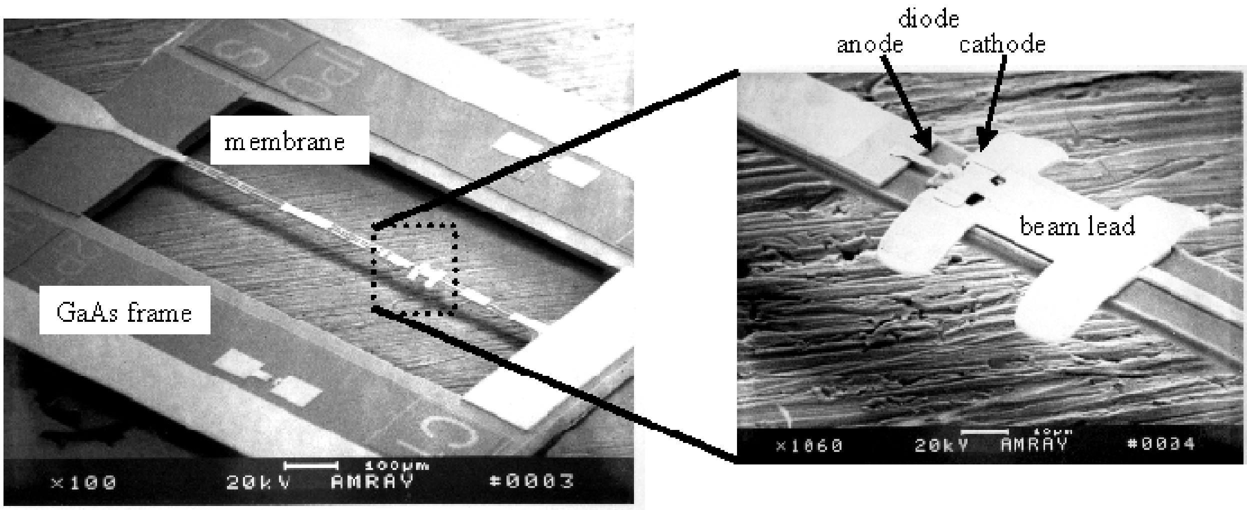

Fig. 1. Left (1a): SEM photo of the MoMeD circuit. Right (Fig 1b): Close up of the diode and the beam lead on the membrane.

The planar Schottky diode and the RF filters are defined on top of the membrane (Figure 2), which is suspended at the center of a 50x50 μm^2 rectangular channel. The cutoff frequency for this channel is 3 THz. Therefore only the propagation of a coaxial mode through the membrane is possible. This mode is transformed into a TE fundamental waveguide mode at the output, where the diode is defined, and at the input where an E plane probe is located. The waveguides are separated by a distance of 250 μm and orientated perpendicular to the membrane [Fig. 2]. Between the waveguides an input band-pass filter is implemented which passes the fundamental frequency and rejects the second and third harmonics. To provide the diode with DC bias an input band-stop and RF/DC short (including λ/4 band-stop) were necessary. The GaAs frame supports the bias return and the DC bias beam lead for connection off the frame.

The ability to bias the diode is important for monitoring the coupling of input power and optimization of the output power while the diode is operating mainly in the resistive mode.

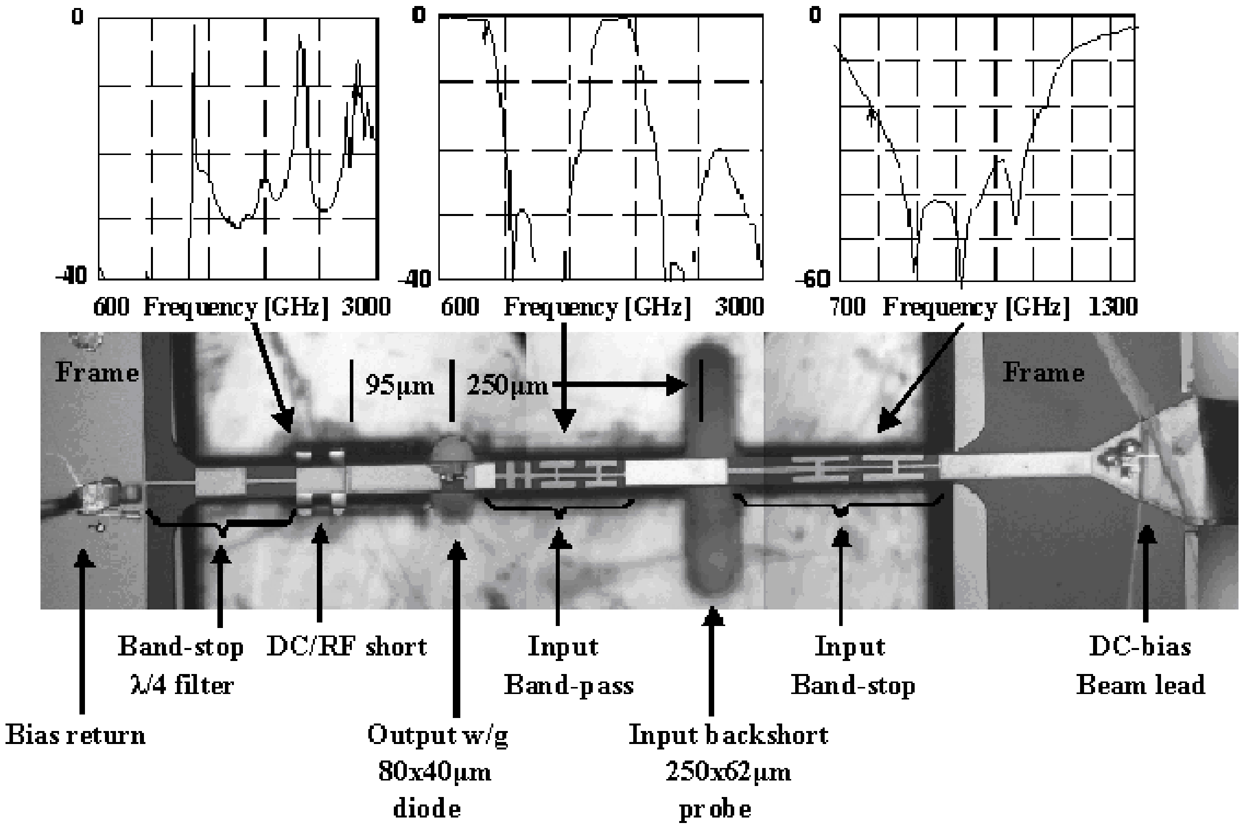

Fig. 2: MoMeD circuit and filter performance (modelled). Top: Filter responses of: the RF/DC short including λ/4 band-stop (left), the band-pass (middle), and the band-stop (right); Bottom: Mounted single diode circuit close up.

Two circuits using different diode configurations were designed and implemented on the membrane. One configuration has a single submicron diode (Fig. 1b) and the other consists of an antiparallel diode pair arrangement. The antiparallel pair circuit generates only odd harmonics and is similar to designs used at lower frequencies [8]. In both configurations the diodes are defined in the output waveguide, which is cutoff at the second harmonic. The antiparallel diode pairs are centered in the output waveguide while the single diode circuits include variations with the diodes centered, as well as next to, the output waveguide wall. During the circuit simulations both locations were found to have reasonable performance. The complete MoMeD circuit integrated in the filter channel (Figure 2) was simulated using a high frequency structure simulator (HFSS) as well as modeled on an X/Ka band mockup (1:135 scale) with commercial beam lead devices. For simulating the individual filter response we also used an electromagnetic simulator based on conformal finite-difference time-domain (FDTD) [9]. Final locations for the filter elements followed more detailed non-linear numeric analysis in Microwave Design System (MDS) [10] with the diode model developed in [11]. In order to compensate for inaccuracies in the diode model at frequencies above 500 GHz we varied the anode size on the GaAs wafer. The single diode designs have anodes of 0.4 to 0.8 μm^2 (Cjo varies from 1.1 fF to 2.5 fF) and the antiparallel diodes have a nominal anode area of 0.5 and 1 μm^2 (C_{j0} = 1.25 fF, 2.5 fF) per anode.

During the simulations it was found that the position of the RF short on the membrane had a large effect on the predicted conversion efficiency. Therefore we implemented two variations of the RF/DC short position to define a virtual ground at the wall of the output waveguide. One variation has the beam lead ground exactly at the output waveguide wall and the other has it λ/2 (95 μm) away, as shown in figure 2. Likewise the input band-stop filter was found to impact the band-pass filter response between the input and output waveguides significantly. A further constraint was to design the filters to be as compact as possible to reduce high frequency losses. Therefore we used a combination of hammerhead [3] sections and high-low impedances. All filters were first optimized separately and then integrated in the MoMeD circuit design. One challenge was to reduce the interaction of the filter elements. By iteratively changing the relative position and slightly varying the filter element dimensions we were able to move the undesirable resonances out of the desired frequency bands (fundamental, 2nd, and 3rd harmonic).

WAVEGUIDE BLOCK

The housing for the MoMeD circuit (Fig. 3) was designed to minimize mechanical complexity. It employs an unusual split-block configuration in which the waveguides lie parallel to one another (Fig. 4). Dual mode horns are integrated in both parts of the split block. The MoMeD circuit is mounted in the half which contains the output horn. When the blocks are joined together they can be optically aligned using a microscope viewed through the horn aperture. The precision for this procedure was better than 5 μm.

Fig. 3: Assembled MOMED tripler. The outer block dimensions are: HxWxL = 16 x 20 x 10 mm (without the SMA connector).

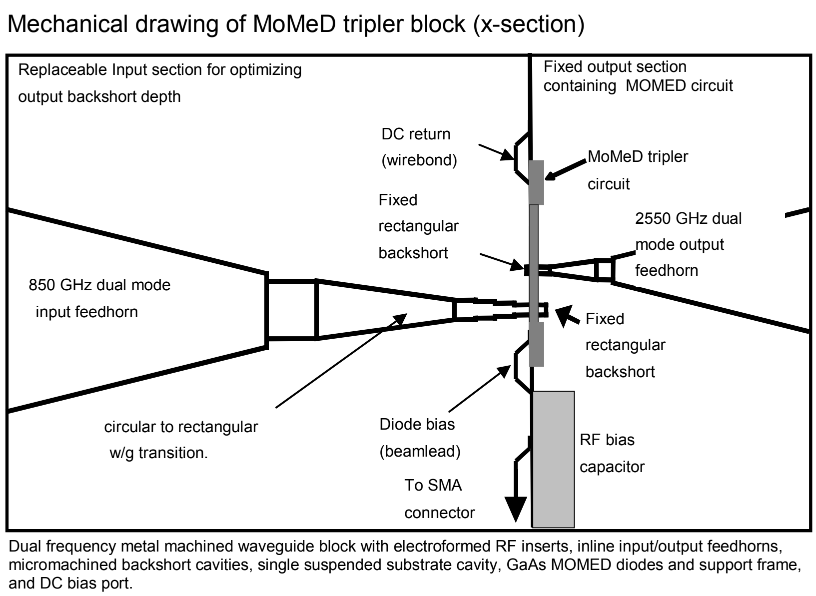

Fig. 4: MoMeD multiplier block shown in cross section.

Power coupling at the input and the output of the MoMeD circuit is accomplished with dual mode Pickett-Potter feed horns [12]. We machined the horns, together with a short waveguide section, in an aluminum mandrel (Fig. 5). After the machining, the mandrels were electroformed with copper and the aluminum was etched out. The finished copper inserts were then pressed into a bore hole in the two halves of the split block.

The horns and waveguide transitions were analyzed with the aid of an electromagnetic simulator (HFSS). The calculated return loss of the rectangular-to-circular transition (left in Fig. 3) is better than 20 dB. Note that the input waveguide is ½ height to reduce the impedance for better diode matching. The return loss for the output transition was better 30dB.

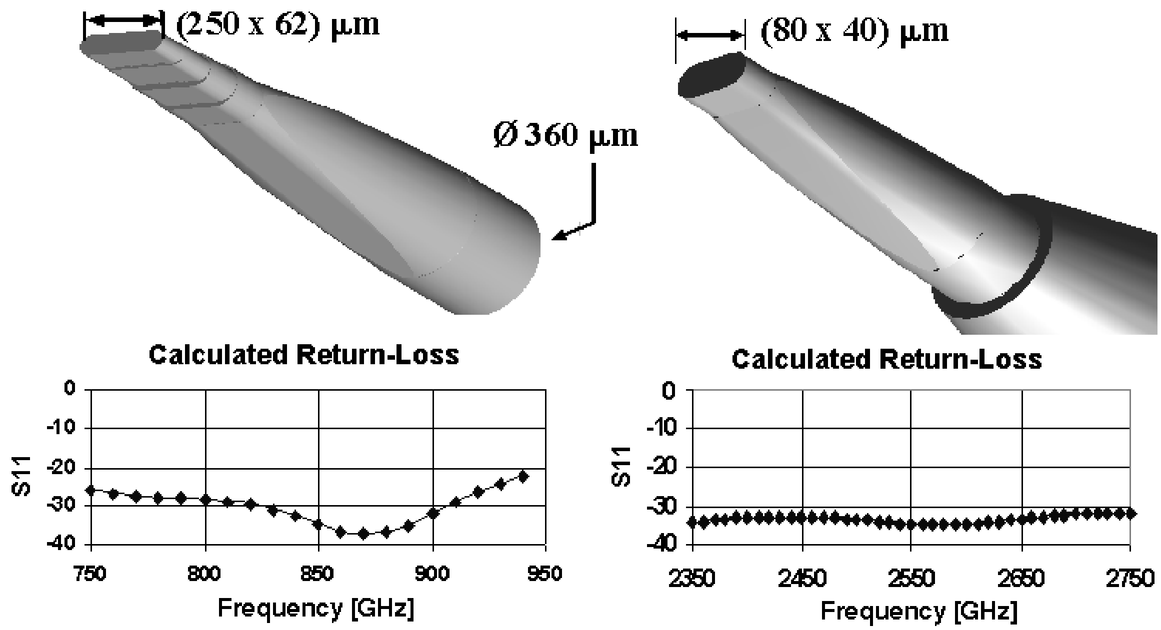

Fig. 5: Calculated return-loss of input and output circular to semi-circular-sided waveguide transition.
Left: The input transition with integrated full height to reduced height waveguide transformer is displayed. S11 is better than 20dB.
Right: The output transition with a part of the output feedhorn is also displayed. S11 is better than 30dB.

In order to house the MoMeD circuit, a relief hole was machined into the output block as shown in Fig. 6. The output backshort cavity depth was varied in several blocks and machined directly into the opposite block half. A similar cavity was milled in the half containing the device to serve as an input tuning short. The suspended substrate channel with a cross section of 50x50 μm^2 was milled only in the output block. The channel crosses the output waveguide and the input backshort cavity at their centers and accommodates the membrane of the MoMeD circuit. The membrane is mounted at the vertical center of the suspended substrate channel with an accuracy of better than 2 µm. Cyanoacrylate glue was used to hold the MoMeD circuit in the output block. The DC bias input beam lead formed on the GaAs frame was bonded to a capacitor. A bond wire connects the capacitor with the center pin of an SMA connector. The beam leads on the membrane itself were intended to provide both DC and RF shorts near the output waveguide, but they did not always provide adequate contact, hence extra bond wires were connected from the MoMeD frame to ground.

Variable depth waveguide backshort cavities (Fig. 2) were directly micro-machined into both halves of the split block. The depth of the output backshort was varied in steps of 0, 10, 20, 30 and 45 µm with a cross-section of 80x40 µm. The input backshort cavity in the output block (Fig. 6) has two different depths, 175 µm and 95 µm. Its cross-section is 250x62 µm. The direct machining simplified the block fabrication and allowed the backshort cavity to be positioned within 2 µm total accuracy relative to the waveguide of the feedhorn (Fig. 6). However this design means many separate blocks are required to perform RF tuning. Because the tuning shorts were cut with a single pass of an endmill whose diameter was equal to the waveguide height, the resulting guide has semi-circular-sided broad walls. In order to reduce mismatch, the same shape was machined into the waveguide sections of both horn mandrels (Fig 5.). A similar waveguide is used on the much lower frequency Pacific Millimeter power detectors. Simulations indicate that the width must be increased slightly over that of a straight sidewall rectangular waveguide to match the desired cutoff frequency [13], but the performance is otherwise unaffected.

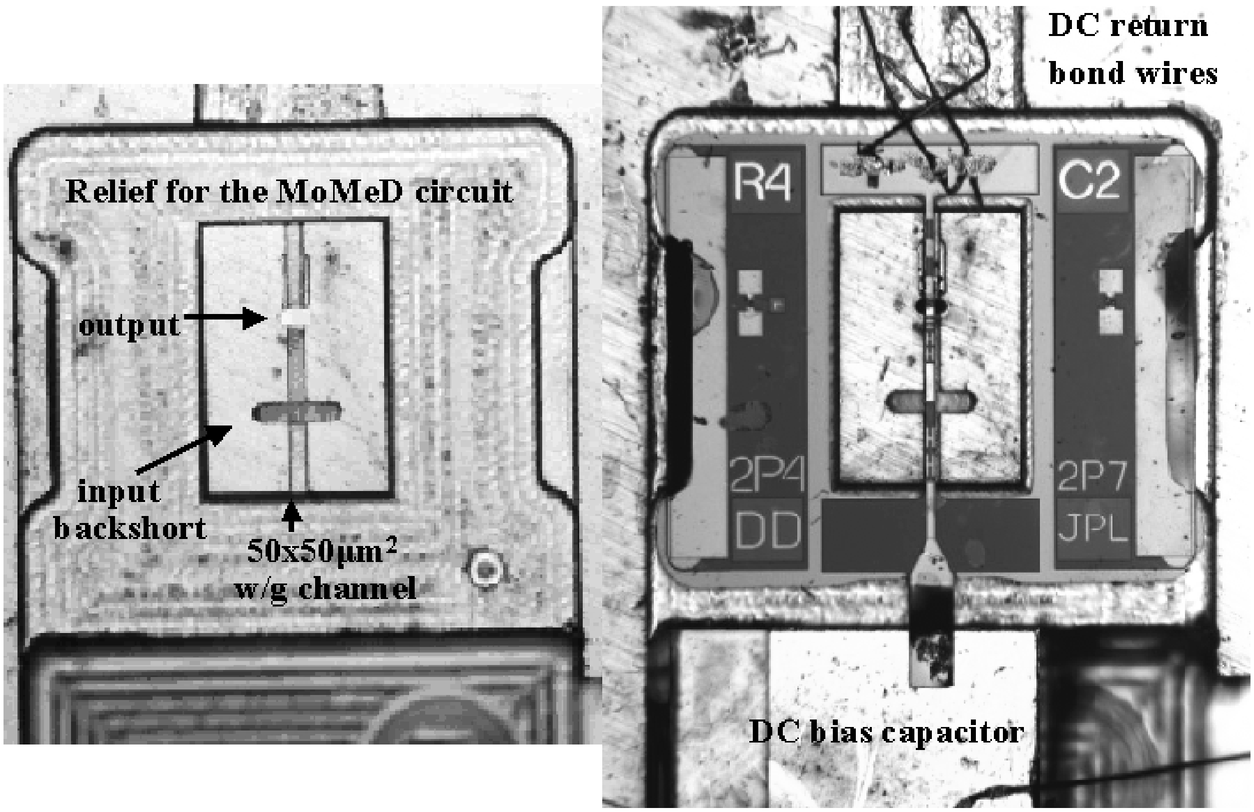

Fig. 6: Output block of the 2.7 THz tripler, with mounted MoMeD circuit.
Left side: A relief with approx. 100 µm depth for the MoMeD circuit is shown, the output waveguide (80x40 µm) is lightened, the 50x50 µm rectangular waveguide is crossing the input backshort cavity (250x62 µm) and the output waveguide in the center.
Right side: Assembled MoMeD device. On the top the bias loop is grounded, on the bottom there is the bias capacitor and the bond wire to the SMA visible.

To optimize the output power, the depth of the input waveguide cavity was varied by swapping block halves. To optimize the input power similar MoMeD devices were used in a series of blocks each with a different cavity depth for the input waveguide. The diodes bias current was monitored in video detection mode for these measurements. The advantage of this split-block arrangement is short input/output waveguide lengths. Although the calculated waveguide loss at 2.5 THz is very low (<.05 db/100 microns [14,15]), the actual measured loss will be much higher.

MEASUREMENT SYSTEM

The tripler measurement setup is shown in Figure 7. As no solid-state source was available at the time, a strong (>100W) carbon dioxide (CO_2) laser [16] was used to pump a far-infrared (FIR) laser. Sufficient output power of the FIR laser at two frequencies in the range from 780 to 900 GHz was produced to pump the tripler. A Fabry Perot filter was used to stabilize the CO_2 laser at the selected pump frequency. The output power of the FIR laser was measured with a commercial power head with 30% accuracy, since it could not be calibrated for this frequency range. The FIR output was mechanically chopped and focused into the input horn of the tripler. The output power of the multiplier was detected with a 4K-cooled Silicon-bolometer in direct detection video mode. A pre-amplifier with 200x and 1000x magnification is integrated on the cold stage of the bolometer. With a magnification of 200x the bolometer was calibrated at 2.5 THz. The measured sensitivity was $Rv=(5.5\pm1.0)\times10^5$ Vp-p/W. To shorten the output path the detector was mounted as close as possible to the output feedhorn of the tripler. This was necessary since a strong water absorption line at 2523 GHz is present. Further we suppressed standing waves by placing absorber strategically around the input window of the detector. Output power was optimized by adjusting the DC bias on the diode.

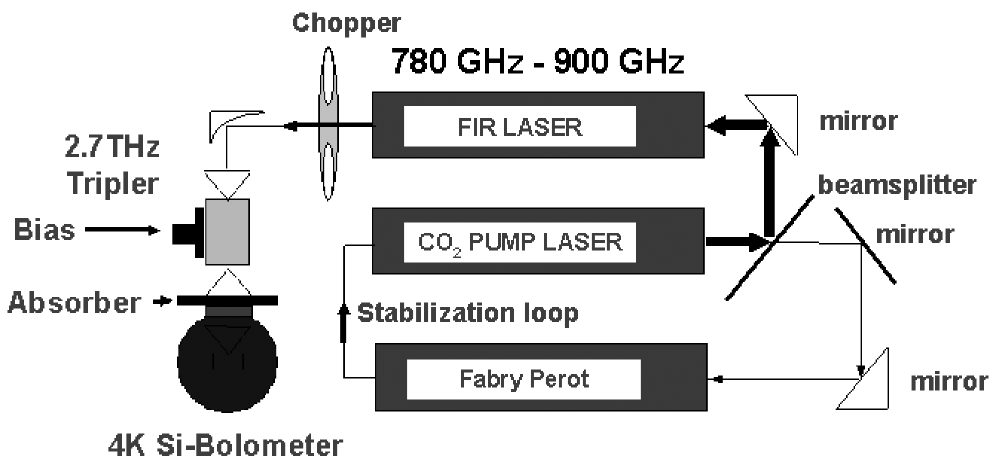

Fig. 7: FIR laser tripler test setup.

RESULTS

Preliminary results were obtained with two single diode circuits mounted in the waveguide block. In both cases the anode size was 0.4 x 1.9 μm^2 (C_{j0} = 2 fF). The RF/DC short was placed at a distance of 94 µm from the waveguide wall as displayed in Fig. 6. Typical measured device I/V characteristics are: series resistance $R_S = 6\ \Omega$, saturation current $I_{sat} = 1\times10^{-12}$ A, and ideality factor $\eta = 1.5$.

We used the 10R16 line of carbon dioxide (CO_2) to pump deuterated methanol (CD_3CD). The measured output power at 850 GHz was (6±2) mW. With this power the diode bias point at constant bias voltage was driven from 10 µA (with no input power) to more than 1 mA. The output signal from the tripler was detected with the Silicon bolometer. With the pre-amplifier set to 200x, the output voltage was 50 to 60 mV. This corresponded to an output power of about. 0.1 µW at 2550 GHz. The tripler was also measured using a deuterated formic acid (DCOOD) line pumped by the 10R12 line of CO_2 (110 W). The FIR laser generated (7±2.5) mW at 787 GHz. Our best estimate of the tripler efficiency and output power (available input to detected output) is 0.0003 % and 0.025 µW at 2360 GHz and 0.002 % and 0.1 µW at 2550 GHz. Currently only two single diode and one antiparallel-pair diode circuits have been measured. At this point only the single diode circuit can be pumped sufficiently to generate measurable output power above 2 THz.

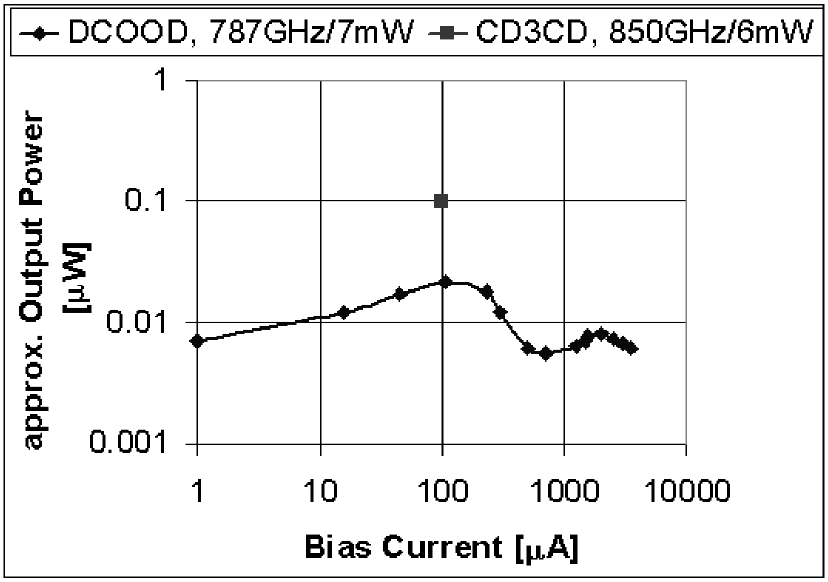

Fig. 8: Measured performance (approximate output power vs. bias current) of the MOMED tripler at 2361 GHz and 2550 GHz at fixed input power. Maximum output power was obtained at 100 µA and 0.7 V bias.

We also investigated the video responsivity as well as the isolation between the input and output horns. The output waveguide tuning cavity depth was optimized in this way. A cavity depth of 20 µm (λ/4) was optimal. Fourth and second harmonic content were checked by measuring the output standing waves when the detector was moved with a micrometer mount along the propagation axis. Harmonic content was below detectable limits.

SUMMARY

The first measurements of a 2.7 THz planar diode frequency tripler have been reported. By pumping with a laser source at 850 GHz, we estimate that 0.1 µW was detected at 2550 GHz. Although the conversion efficiency is very poor and the output power is low, the circuit and device topology are robust and there is much room for improvement. Further research is needed to find a more accurate way to measure the power at THz frequencies. The device structure is identical to that used for THz mixing and it has been qualified for flight [1, 17]. It is expected that similar circuit realizations could be used for multipliers at other frequencies in the submillimeter regime in order to produce flight qualified all-solid-state sources. Additional measurements are in progress, over a greater frequency range, and with other design variations available on the mask set.

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