2.7 THz Waveguide Tripler using Monolithic Membrane Diodes

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***Abstract* – The description and performance of an 850 to 2550 GHz waveguide tripler is presented. The tripler utilizes GaAs monolithic membrane diodes (MOMED) in single and antiparallel pairs. Output power of ≈0.1μW is reported.**

I. INTRODUCTION

The most sensitive high spectral resolution detectors in the submillimeter-wave range rely on heterodyne downconversion for both optimal signal-to-noise ratio and almost unlimited frequency resolution (required for profiling spectral lines). Whether employing superconductor or semiconductor mixers, heterodyne receivers in the submillimeter are currently crippled by the lack of available pump sources to serve as local oscillators (LO) - essential to the downconversion process. For semiconductor mixers 0.5 to 5 mW per receiver is needed. Superconducting SIS and HEB (hot electron bolometer) mixers require much less LO power (1 to 50 μW), but even this power level is difficult to produce above 600 GHz and has only recently been demonstrated with an all solid-state source up to 1.2 THz [1,2,3].

In this short paper the authors report a first attempt to reach into the high submillimeter with an all solid-state source that can produce enough power to drive a superconducting receiver. Specifically we describe an 850-to-2550 GHz planar diode frequency tripler implemented in single mode rectangular waveguide.

II. CIRCUIT TOPOLOGY

In order to keep the device configuration as simple as possible we adopted the MOMED (monolithic membrane diode) fabrication technique developed earlier in our laboratory for THz mixer applications [4-6] [Fig. 1]. The circuit is configured such that the multiplier input and output waveguides are formed parallel to one another with access to the device via an unusual split block arrangement [Fig. 2]. As in the mixer circuit of [5], the MOMED device membrane [Fig. 3] crosses the propagating mode plane and, in the tripler, spans both the input and output waveguides. Appropriate RF filters behind and between the two waveguides perform impedance matching, and selective blocking or passing of the harmonic frequencies [7]. The filters lie suspended at the center of a single mode 50x50 μm cross section TEM channel and are composed of metallic hammerhead elements printed on the 3 μm thick by 30 μm wide by 700 μm long GaAs membrane. Following a suggestion by [8] to help with bandwidth, an RF/DC short is implemented directly behind the output waveguide using freestanding metallic beam leads projecting off the sides of the membrane. An additional DC short is implemented beyond the thick (50 μm) GaAs frame using a separately attached wire bond that shorts to the metallic waveguide block. On the opposite side of the circuit, a DC bias line is implemented through a beam lead formed on the GaAs frame. The bias line is bonded to a capacitor and then to the center pin of an SMA connector. Typical device IV characteristics are: R_s=6 Ω, C_{j0}=2 fF, I_{sat}=1x10^{-12} A, η=1.5. The epilayer is doped 5x10^{17} cm^{-3} and is 100 nm thick.

The split block is unusual in that the lower half contains both an electroformed output feed horn and a short blind waveguide cavity that serves as an input waveguide tuner. The upper half contains an electroformed input feed horn and a blind waveguide cavity forming an output tuner. The MOMED chip and bias lines are contained in the lower half. Tuning is accomplished first by optimizing the depth of the input waveguide cavity in the lower block half by using similar MOMED devices in a series of blocks each with a different cavity depth. Output tuning is performed by swapping out input horn blocks with different output cavity depths over the same input block and device. This process requires several blocks, each with identical feedhorns. However, since all the waveguide cavities and filter slots can be milled directly on the copper horn electroforms with precision NC micromachining, it is a relatively easy operation to make multiple copies of the circuit with different backshort cavity depths. The advantage of this arrangement lies in very short input/output waveguides, no crossing of the waveguides with the membrane frame and an inline input/output structure. High beam quality dual mode Pickett-Potter feed horns [9] are used at both 850 and 2550 GHz. The horn and full length of joining rectangular waveguide are formed in an aluminum mandrel and electroformed into copper. No problems were encountered in wet etching the aluminum from the electroform. A photo of the assembled block is shown as Fig. 4.

In order to allow the waveguide backshort cavities to be milled directly on the horn electroforms, a semi-circular sided rectangular waveguide is employed similar to that used on the much lower frequency Pacific Millimeter detectors. The waveguide width is increased slightly over that of straight sidewall rectangular waveguide to match the cutoff frequencies [10]. Using 50 μm diameter commercially available end mills, it is possible to directly machine the half height 850 GHz and full height 2550 GHz waveguides to a depth of approximately 1/2 wavelength.

Assembly of the MOMED chip is straightforward and follows the same procedures used for the MOMED mixer circuit reported in [5]. Alignment of the input and output waveguide shorting cavities and horns is accomplished under an optical microscope in a matter of minutes using alignment marks on the block halves and visual inspection through the waveguide feed horns. An accuracy of 5 μm is readily obtained. Cyanoacrylic is used to hold the MOMED in place and wire bonds are used to connect the bias and DC return. The beamleads along the membrane are supposed to provide both DC and RF shorts near the output waveguide, but do not always provide adequate contact, hence the extra bond wire on the MOMED frame.

III. Circuit Description

Two diode configurations are utilized in the tripler – a single device spanning the output waveguide with the second harmonic cutoff in the output cavity, and a dual diode antiparallel pair arrangement similar to designs used at lower frequencies [11] which generates only odd harmonics. The circuit was simulated using HFSS as well as modeled on an X/Ka band mockup using commercial beam lead devices. Final locations for the filter elements followed more detailed numeric analysis in MDS using the diode models developed in [12]. Several circuit variations were implemented when it was found that the position of the RF short on the membrane filter had a large effect on the predicted conversion efficiency. Likewise the RF blocking filter on the DC side of the input waveguide was found to significantly impact the band pass filter response between the input and output waveguides (due to the requirement to have a continuous DC path from the bias port across the input waveguide and to the diode). Actual simulation results are given in [7].

IV. Performance

The first measurements on the tripler were made using a 2.5 THz laser pump source [6]. Input power coupling to the diode was measured by injecting laser produced power at 118 μm into the output horn. Rough video responsivity was checked as well as isolation between the input and output horns. The output waveguide tuning cavity depth was optimized in this way. As no solid-state source was available to us at the time, another laser pump source [13] was used to generate 850 GHz radiation via deuterated methanol and 787 GHz via deuterated formic acid, both pumped with a strong CO_2 laser. Input power was measured to be 6 mW at 850 GHz and 7.5 mW at 787 GHz on an uncalibrated IR sensor head. Output power at 2550 GHz was detected with a helium-cooled bolometer. Fourth harmonic content was checked and found to be below detectable limits. Our best estimate of the tripler efficiency and output power (available input to detected output) at the current time is 0.0003% and 0.025 μW at 2360 GHz [Fig. 5] and 0.002% and 0.1 μW at 2550 GHz. To date only two circuits have been tested and we have not yet measured the performance of the dual diode devices (expected to have higher efficiency, but require larger pump power).

V. Summary

The first measurements of a 2.7 THz planar diode frequency tripler have been reported. Pumping with a laser source at 850 GHz, we estimate 0.1 μW was detected at 2550 GHz (although this must be confirmed by further measurements). This power level may be sufficient to drive a superconducting heterodyne HEB (hot electron bolometer) downconverter [14]. Although the conversion efficiency is very poor and the output power low, the circuit and device topology are robust and there is much room for improvement. The device structure is identical to that used for THz mixing and has been flight qualified. It is expected that similar circuit realizations could be used for multipliers at other frequencies in the submillimeter to produce flight qualified all solid-state sources.

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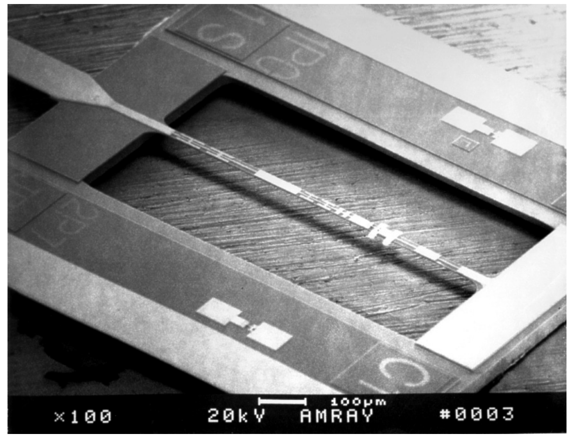


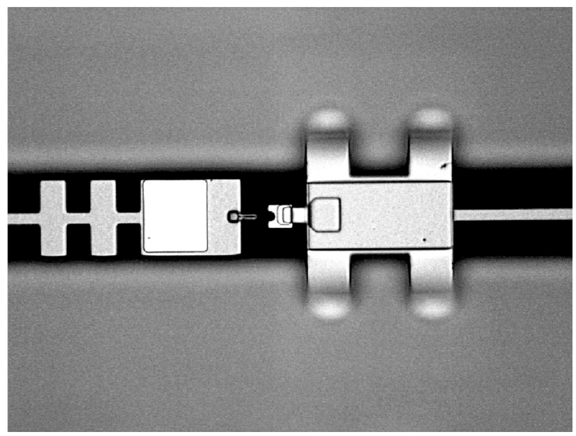
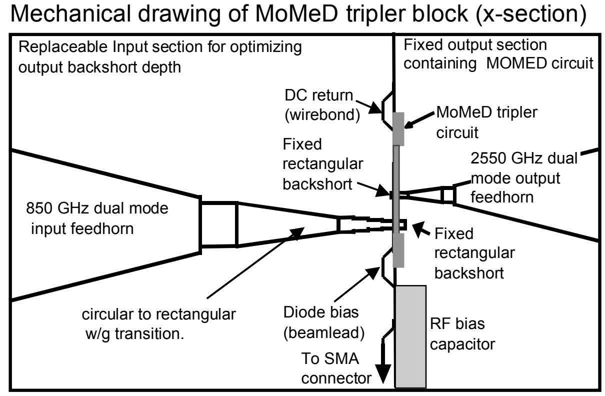


Fig. 1. Top: SEM picture of MOMED circuit showing GaAs membrane bridge and frame. Below: Close up of 2.7 THz diode and RF short.

Mechanical drawing of MoMeD tripler block (x-section)



Dual frequency metal machined waveguide block with electroformed RF inserts, inline input/output feedhorns, micromachined backshort cavities, single suspended substrate cavity, GaAs MOMED diodes and support frame, and DC bias port.

Fig. 2. Mechanical layout of the MOMED tripler split block shown in cross section through the center.

Fig. 3. Left: MOMED tripler shown mounted in waveguide block lower half. Output waveguide is above center, input backshort cavity below center. Right: Blow up showing output waveguide region with mounted antiparallel-pair membrane diodes.

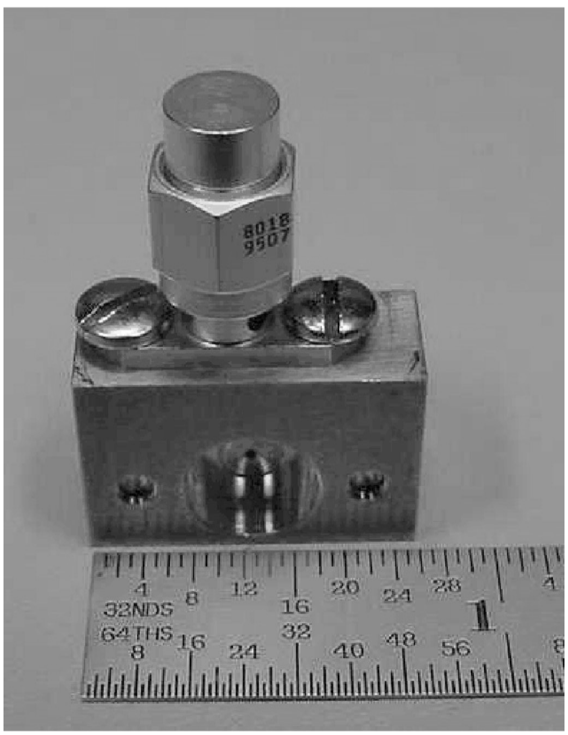


Fig. 4. Photograph of assembled MOMED tripler block showing output feed horn and bias connector.

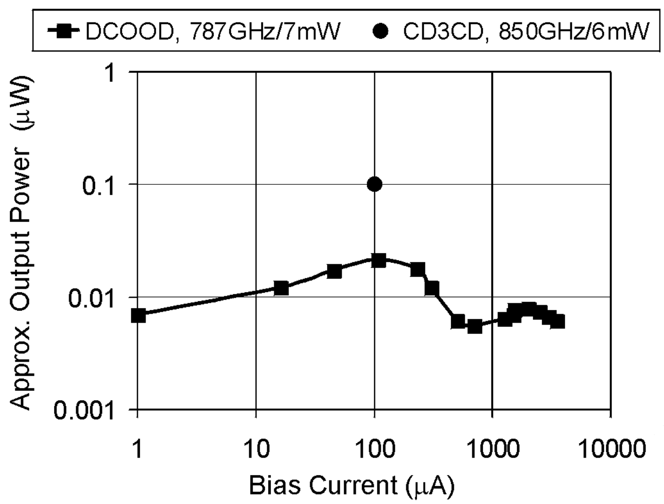


Fig. 5. Measured performance graph (approximate output power vs. bias current) of the MOMED tripler at 2361 GHz and 2550 GHz at fixed input power. Maximum output power was obtained at 100 μA and 0.7 V bias. Estimated input power from the pump laser at 787 GHz was 7 mW. Estimated output power based on the detector responsivity is ≈0.025 μW. Measurements made at 850 GHz input using deuterated methanol with an estimated input power of 6 mW result in output voltages of 50-60 mV on the detector corresponding to an approximate power of 0.1 μW. Further measurements on different single and antiparallel diode configurations are in progress.