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# HIGH EFFICIENCY MMIC FREQUENCY TRIPLERS FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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## ABSTRACT

A complete wideband tripler circuit with optimized input, idler and output matching has been integrated onto GaAs. The circuit consists of a matched pair of antiparallel varactor diodes with provision for DC bias. The input impedance is near 50Ω in microstrip, while the output couples directly to reduced height waveguide. Circuits have been fabricated and tested for frequencies near 300 GHz. These triplers achieve a peak efficiency of 11% with a power output of 5-7 mW. While peak efficiency occurs over a narrow band, the efficiency exceeds 1% over a band of 230-325 GHz.

## INTRODUCTION

Frequency multipliers are essential for nearly all microwave systems above ~100 GHz because of the nearly complete absence of fundamental sources. Until recently these have all required the use of discrete components, either beam lead or flip-chip planar diodes at the lower frequencies, or whisker contacted diodes at higher frequencies. While circuits have become increasingly sophisticated, the assembly process is still tedious and requires very skilled labor. Circuit implementations are also limited by the requirements to work with discrete devices. A high degree of integration is preferred in order to assure an optimized assembly, and much higher reliability. This is particularly important for space flight applications. In this new work, a complete frequency tripler has been fabricated on a single GaAs wafer, requiring minimal critical assembly, and achieving efficiencies higher than for any previously reported design using discrete parts.

Frequency triplers are relatively complex circuits to design because of the simultaneous requirements to achieve impedance matching in three frequency bands. They become even more complex for use over wide bandwidths. The equivalent circuit of a varactor diode is a series resistor and capacitor, with the capacitance nearly frequency independent, and the resistance comparable at the input and output frequencies. The circuit Q ($1/\omega RC$) is about 5-6 at the input, dropping to ~2 at the output, and these high Q circuits produce their own bandwidth limitations. Varactor triplers also require a nearly resonant lossless inductive termination at the second harmonic. Tuning out the capacitance at the three frequencies is the most difficult problem, since the circuit's inductive reactance must decrease rapidly with frequency.

Tripler circuits also require filters to separate the harmonics, and this requirement is eased through the use of balanced designs having antiparallel pairs of diodes, which trap even harmonics within the diode loop. Filtering is only needed to separate the input and output, which are widely separated. Varactor diodes require bias for efficient operation so the diode loop must include a DC block and bias terminal.

## CIRCUIT DESIGN

The circuit which was developed to meet these requirements is shown in Fig. 1. The circuit was designed with the aid of HFSS [1], and required many simulations to determine circuit parameters. Because simulations of such a complex structure are slow, the circuit is not well optimized, and this version was viewed mostly as a proof of concept. The requirement for which it was designed needed only a 12% bandwidth.

The diodes are in antiparallel, with a DC break provided by an overlaid pair of lines with dielectric isolation on the output side of the circuit. Bias is applied to the diodes in series. The input is in a microstrip mode with an impedance near 50 Ω, and

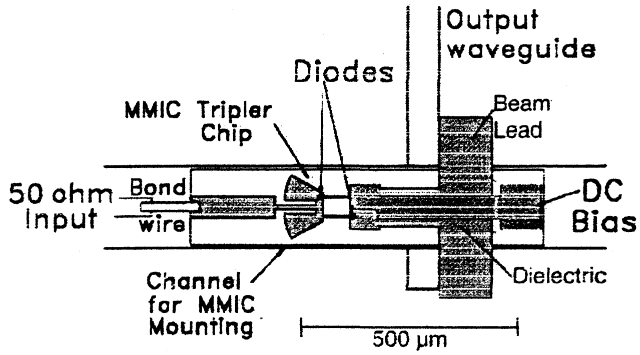


**Figure 1. Drawing of the tripler chip, and its mounting relative to the output waveguide. The output step transformer is not shown.**

may be fed by a waveguide to microstrip transition, or at low frequency, by a coaxial transition. The input must be DC isolated since bias appears on this line. At the input frequency the diodes are in series with a short-circuited stub, which provides the correct input reactance. This stub is grounded using beam leads on the far side of the output waveguide. The output waveguide is cut-off at the input and so no additional filtering is needed at this frequency, but the line crossing the waveguide has very high impedance and so the waveguide must have quite reduced height in order to avoid adding excessive input inductance.

At the output frequency, two radial stubs provide short circuits at either diode, and ensure that little power couples back to the input. At this frequency the input stub line becomes the coupling line to the output waveguide, as well as an impedance matching section. The narrow lines connecting to the diodes provide the required output inductance. Additional impedance matching is provided by a step transformer up to full height waveguide, and by a fixed backshort in the waveguide.

At the second harmonic, the diode loop is tuned to provide nearly optimum inductance at midband without producing excess inductance at the output frequency. In part this is because the second harmonic currents flow in a different path, including transverse currents between the stubs, and across the wide output line. In addition, the radial stubs themselves act as quasi-lumped capacitances and load the loop in a way that increases its second harmonic reactance. The overall effect is an idler tuning which is optimized at midband and remains acceptable over quite a wide band, mainly at frequencies below the design band. At higher frequencies, the idler goes to an open circuit, and the efficiency drops rapidly. The radial stubs add a lot of capacitance at the input, and degrade the match, requiring them to be as short and narrow as possible. This leads to a loss of output power, particularly at low frequencies in the band.

The circuit is in microstrip from the input to the radial stubs and switches to suspended stripline for the remainder of the circuit to avoid moding problems for the higher frequency part of the circuit. The channel housing the chip is significantly wider than the chip to further suppress higher modes. None of the circuit dimensions outside of the chip itself appear to be critical, and even the substrate thickness is tolerant of a wide range of variations. The original design was for 20 μm thickness, but chips on 38 μm substrates also work well, although with different tuning.

## DEVICES

Triplers were designed for center frequencies of 280 and 320 GHz. These chips were fabricated on semi-insulating GaAs with epitaxial doping of $10^{17}$ $cm^3$. The anodes are made as rectangular strips of 1.5x9 μm with a breakdown voltage of 13 V, and a zero bias capacitance of 19 fF. The DC isolation dielectric is 0.1 μm thick SiN. The substrate has no backside metal, meaning that in the region where the mode is microstrip, the chip must be in good contact with the metal of the block.

The mesa etching required for this chip was done using reactive ion etching (RIE), which allows for much better control and repeatability compared to wet chemical etching. The air-bridge part of the device is obtained by using a thermally cured layer of photoresist that allows the air-bridge to have the required curvature without breaking. The anode and air-bridge were fabricated in one step thus minimizing alignment and parasitic capacitance problems.

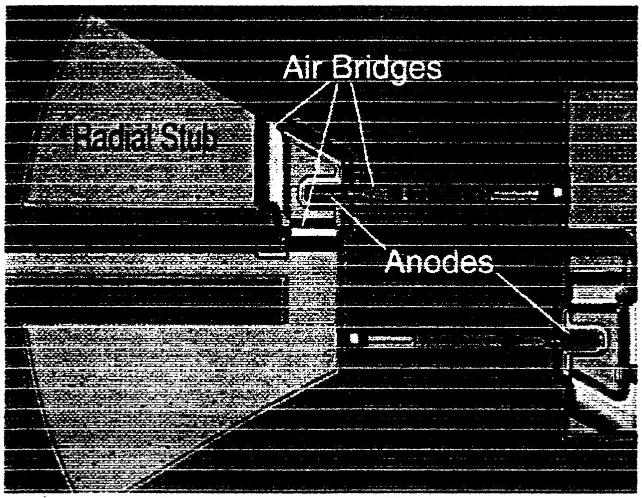


**Figure 2. Anode area of the tripler chip. Air bridges connect the mesas with the lower level.**

Once the topside processing was completed the wafers were lapped down to thicknesses of 20 and 38 μm before the final backside lithography and separation. Chip separation was done by RIE (from the backside) which allows individual devices to be spaced very close to each other and also allows for the use of beam leads and arbitrarily shaped chips. The beam leads are essential to RF and DC ground the end of the chip where little area is available for wire bonding. The devices were fabricated using standard 3-inch wafers resulting in large yields of devices.

The same circuit was fabricated in a scaled version for 500 GHz on a more highly doped wafer, which has not yet been tested. With some modifications, the circuit has been scaled up to 1200 GHz, and is currently in fabrication.

## TRIPLER ASSEMBLY

Machining of the blocks is straightforward and was done on a CNC milling machine. The block is split on the E-plane centerline of the waveguides. The only challenging feature is the output waveguide, which is 70 μm high. The WR10 waveguide to microstrip transition [2] was fabricated on alumina, and is expected to produce a near 50 Ω impedance across the band. The output waveguide uses a step transformer intended to optimize the performance over a 12% band, but the chip design was modified after the blocks were machined and this transformer is no longer optimal even for this band. A photograph of the assembled tripler is shown in figure 3. Chips were glued down with a low viscosity epoxy, and then the beam leads were bonded to the block. Connections were made to the chip by ribbon bonding to the input and bias pads. Assembly was judged to be very easy compared to any other multipliers at a similar frequency.

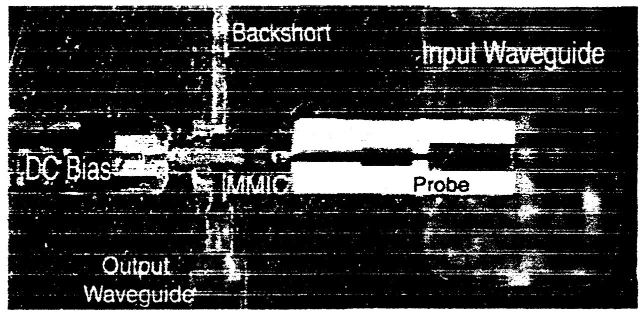


**Figure 3. Photograph of the tripler for 280 GHz, showing the input and output waveguides, the alumina input transition and the bias connection.**

## MEASUREMENTS

Tests have been performed using a wide-band Gunn oscillator source, and some wideband power amplifiers. Bias was optimized at each frequency, and varied from 2 V at frequencies very low in the band, to 6-8 V at the higher (design) frequencies. The results are shown in Figure 3. The highest efficiencies are obtained with an input power of 40-50 mW, although the highest output power is 7 mW at 276 GHz, measured with 130 mW input. The input match varies from 6-10 dB return loss, and probably could be improved with some off-chip matching. The best efficiency of the 320 GHz device is 9%, increasing to 11% with the input mismatch corrected with a tuner. The output match has been measured with a sliding tuner only at 320 GHz, where it is very good. It is expected to be good only in the design band. Output power was measured with a wideband calorimeter sensor with an accuracy better than 5% [3].

The best part of the operating band is very close to the design frequency, and is shifted low in both designs by only 2-5%. The exact tuning is dependent on a number of factors such as the substrate and glue thickness. The difference in performance between the two scaled designs gives an indication of the wafer fabrication and assembly variability. Only these two units have been fully tested.

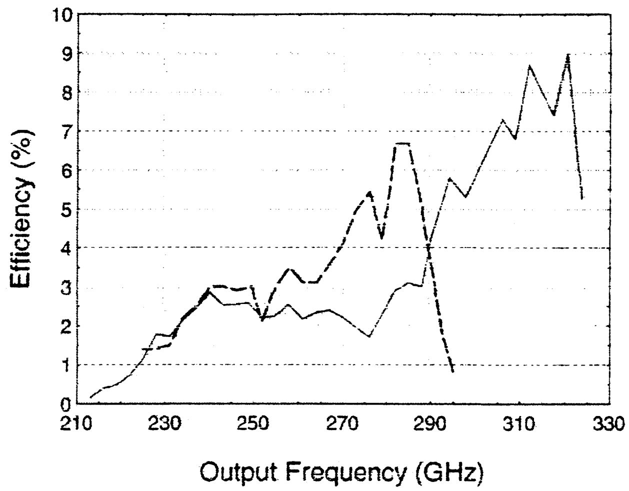


**Figure 4. Conversion efficiency of triplers designed for 280 (dashed) and 320 GHz (solid). Input power varies from 60-100 mW for the 280 design and 40-60 mW for the 320 design.**

The peak efficiency measured at 320 GHz exceeds that obtained with the best whisker contacted triplers at a similar frequency [4], while the bandwidth greatly exceeds that of whiskered devices. Simulations have shown that the same devices could work significantly better over a wider band with a new output waveguide transformer, and the input match could almost certainly be improved with further chip refinement.

The balanced design of this tripler is expected to suppress second harmonic output to a level <-20 dBc even in the presence of ±5% imbalance in diode capacitance. Typically second harmonic output is a serious limitation to the useful bandwidth of triplers. At 315 GHz, where the second harmonic propagates within the output waveguide, it could not be detected with a spectrum analyzer which readily detected the third harmonic.

The 320 GHz tripler survived cooling to 80 K, and its efficiency at 312 GHz increased to 14%, with 7 mW output. The bandwidth was verified using a input source consisting of a WR10 tripler followed by a wideband medium power amplifier (25-40 mW output) [5]. The source was swept over an output band of 240-324 GHz with a minimum output of 0.3 mW at fixed bias.

## CONCLUSIONS

Triplers using MMIC circuits have achieved record high efficiencies and bandwidths near 300 GHz. Assembly and machining are relatively simple. Scaled devices have been fabricated for 500 GHz and are awaiting testing, while much higher frequency devices appear feasible. These triplers move MMIC technology up into the submillimeter region, and will be used to produce space qualified submillimeter local oscillators. They also may enable the production of submillimeter test equipment and wideband LO sources at relatively low cost.

## ACKNOWLEDGEMENTS


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