Monolithic THz Frequency Multipliers

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Introduction

Frequency multipliers are required as LO sources for frequencies up to 2.7 THz for FIRST and airborne applications. Multipliers at these frequencies have not previously been demonstrated, and the object of this work was to show whether such circuits are really practical. A practical circuit is one which not only performs as well as is required, but also can be replicated in a time that is feasible. As the frequency of circuits is increased, the difficulties in fabrication and assembly increase rapidly. Building all of the circuit on GaAs as a monolithic circuit is highly desirable to minimize the complexity of assembly, but at the highest frequencies, even a complete monolithic circuit is extremely small, and presents serious handling difficulty. This is compounded by the requirement for a very thin substrate. Assembly can become very difficult because of handling problems and critical placement. It is very desirable to make the chip big enough to that it can be seen without magnification, and strong enough that it may be picked up with tweezers. Machined blocks to house the chips present an additional challenge. Blocks with complex features are very expensive, and these also imply very critical assembly of the parts. It would be much better if the features in the block were as simple as possible and non-critical to the function of the chip. In particular, grounding and other electrical interfaces should be done in a manner that is highly reproducible.

A complete realization of all of these desires is not presently possible, but we can come fairly close. The primary contribution to the solution is to fabricate all circuitry on 3 μm thick GaAs, and add to this a 50 μm thick frame to support it and provide a handle [1]. The thin GaAs is separated from the thick substrate by an etch stop layer, and so the fabrication of this structure is quite practical. The 3 μm membrane is surprisingly robust, and while it can not be touched by hand, it can contact the block and have beam leads for grounding. An external connection for DC bias may connect to the frame, which is much stronger. Figure 1 shows a framed circuit for a THz doubler, which incorporates a side arm to the circuit membrane in addition to the beam leads.

The metal mounting block provides a frame holder, and waveguides to external interfaces. With the correct circuit design the exact placement of the circuit in the block is not excessively critical, although with THz circuits, even this reduced sensitivity still

demands micron level accuracy. The blocks are in general much simpler to machine than those involving frameless circuits, because the block does not need to touch the membrane, and most clearances can be made fairly generous. Beam lead grounding can be designed to bridge an expected gap.
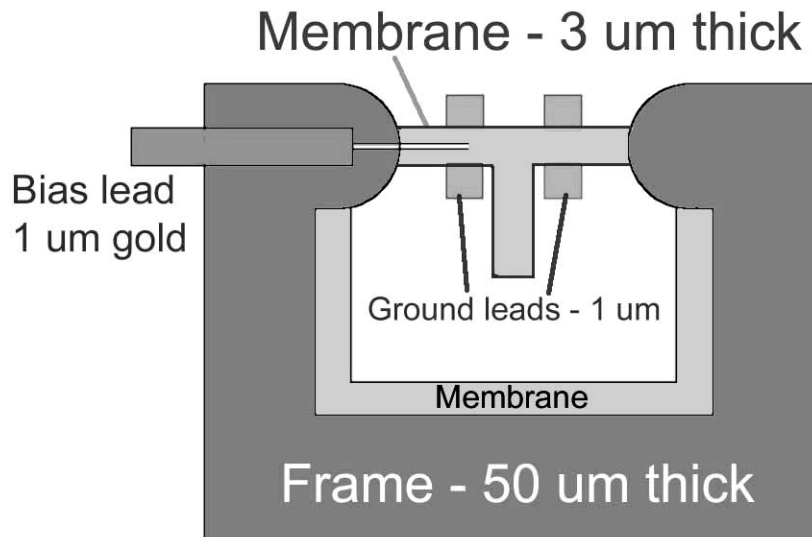

Figure 1.   A membrane and frame circuit showing typical features. This circuit is used for a doubler, but the tripler uses similar features.

THz Circuits

Bands from 0.5 - 2.7 THz are required for the FIRST mission, and performance of planar circuits above 1 THz is largely unknown.   For this reason test circuits were designed for a range of frequencies corresponding to actual required bands from 1 to 2.7 THz. Triplers were designed for 1.0 and 1.2 THz using a varactor balanced design, while doublers were designed for 1.5 and 2.5 THz using a resistive balanced design. Diode properties are essentially unknown at these frequencies but it was believed that the highest practical frequency for varactor operation was around 1 THz.

The design of the circuits is challenging within the constraints, which include a fixed substrate thickness regardless of frequency, an absence of backside metal, and minimum diode mesa dimensions which sometimes exceeded the available circuit space. The completely unknown mechanical behavior of the circuit led to a somewhat conservative design. Despite these constraints, high performance circuits are practical, and suffer no significant limitations beyond those inherent to THz circuits. Design of these circuits requires lots of HFSS simulations to verify operation. Dimensions in nearly all cases are at the maximum limit for higher mode propagation, leading to significant effects from evanescent modes.

Doubler Design

At frequencies near 2 THz, carrier velocity saturation effects seriously limit varactor operation. An approximate value for the peak junction current, estimated from the carrier concentration in the junction, times the maximum saturated carrier velocity, is 3 mA/fF. At 1 THz, a sinusoidal wave has only a 1 V peak-peak amplitude at this current. This means little voltage modulation is possible, and varactor efficiency will be very low. Resistive multiplication requires lower voltage amplitude, and still should work with reasonable efficiency, although it is inherently less efficient. These circuits are required to produce only a few microwatts of output power to drive HEB mixers, and the input power is likely to be very limited as well. Little data is available on multipliers above 700 GHz, and those that have been built have not been intended to produce high power. Projections of optimized drive levels are in the 0.25 to 1 mW level at most. At low power, simulations show that DC forward bias is essential for best efficiency, and zero bias is favored only for power levels far higher than would be available. A balanced design was chosen because it requires no filters, and is very simple, despite the fact that it uses two diodes which double the required input power. Losses in filters can easily exceed the penalty for using two diodes. For the 2.5 THz design, diodes with $C_j(0) = 0.5$ fF were chosen to minimize the required input power. Even smaller diodes seemed desirable but were too far outside the known range for planar diode fabrication. For 1.5 THz, diodes may be significantly larger, at 0.9 fF, and circuit design is easier, because these diodes more closely match the typical circuit impedance levels. Figure 2 shows the predicted efficiency vs. power for a 1.5 THz doubler.
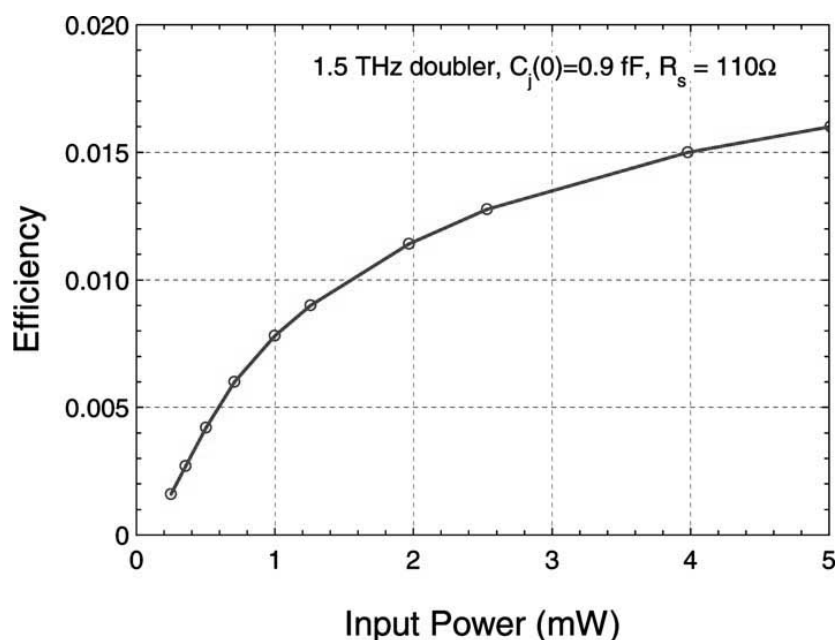

Figure 2. Predicted efficiency vs. input power for a doubler to 1.5 THz using a pair of diodes with $C_j(0) = 0.9$ fF and $R_s = 110\Omega$, biased in the forward direction.

Doubler Construction

A fairly conventional design was chosen in which the diodes are in the output waveguide, for lowest loss at the output frequency. The diodes are easy to bias in series, without affecting RF performance, using an integrated Si_3N_4 capacitor which bypasses the bias circuit. Probe coupling was used in the input waveguide, which requires no contact, and converts the waveguide impedance to a value near 50 Ω. A two section transformer was used to match to the diode impedance in a very short section of quasi-TEM line joining the two waveguides. At the output frequency, the diodes are a fairly good match to full height waveguide without any tuning except the choice of finger length and backshort location, which is close to the diodes. The mounting block provides full height input and output waveguides, a frame holder and a bias connection, with no really critical dimensions. Outside the immediate circuit area, both waveguides step up to square or circular cross sections, which facilitate the further transition to feed horns on both ports. The input has a conical horn while the output uses a diagonal horn. This device was intended to be optically coupled on both ports in initial tests. The closed frame forces the input waveguide to be at a right angle to the frame, and this was the most difficult aspect of this circuit to accommodate in the machining, which did not use electroforming. The inner details of the doubler block and device mounting are shown in Figures 3 and 4. The predicted frequency response for the doubler is shown in Figure 5. The bandwidth is very wide, despite the circuit simplicity, because a doubler operating in a resistive mode has a very low input Q. A flatter response may be obtained in a more optimized block.
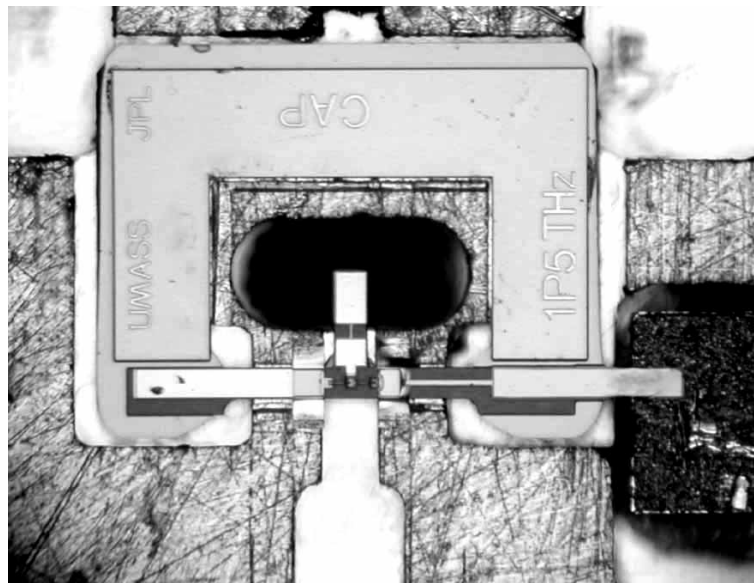

Figure 3. 1.5 THz doubler construction with the device mounted in the doubler block. The device frame surrounds the input waveguide (with rounded corners). The input coupling probe extends into this waveguide, and converts the power to a quasi-TEM mode. The bias beam lead is seen to the extreme right.
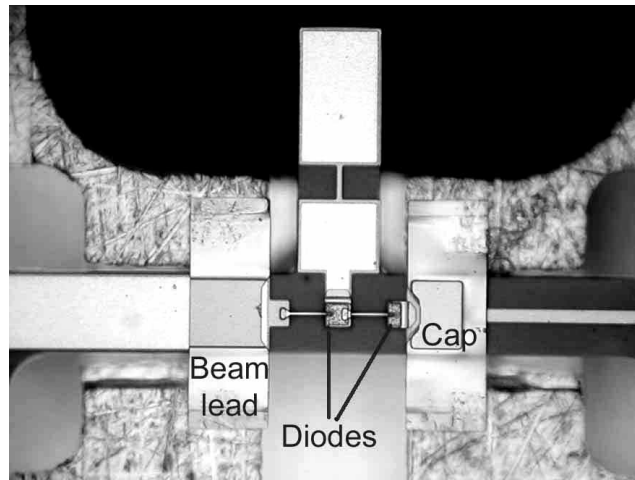
Figure 4. 1.5 THz doubler detail showing the connection of the input probe to the center point between the diodes, which are mounted in the output waveguide. There are four grounding beam leads. The right hand ground includes an integrated SiN capacitor to bypass the bias line.
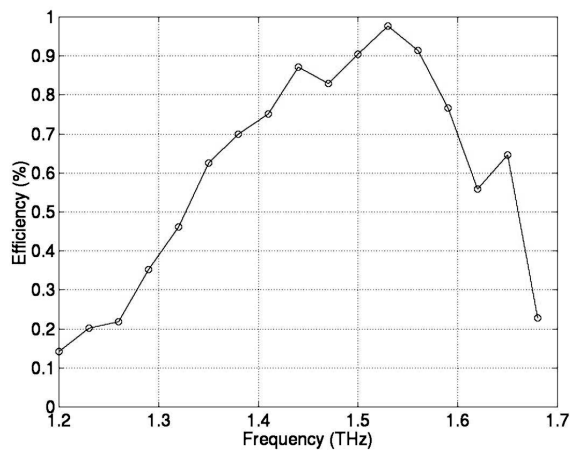

Figure 5. 1.5 THz doubler predicted efficiency vs. frequency at 2 mW input.

Devices

All of the devices were fabricated at JPL on a pair of nominally identical wafers, which included many other designs. The wafer is undoped GaAs having a final thickness of about 50 μm, with an epi structure (grown by MOCVD by Epitronics) as shown in Table 1.

	Mat'l	Thickness	Doping
Epi layer	GaAs	0.15 μm	5.0×10^{17} Si
N++ layer	GaAs	1.0 μm	5.0×10^{18} Si
Etch stop	$Ga_{0.5}Al_{0.5}As$	0.05 μm	undoped
Membrane	GaAs	3.0 μm	$<3 \times 10^{14}$
Etch stop	$Ga_{0.5}Al_{0.5}As$	0.4 μm	undoped

Table 1

An SEM photo of a 1.5 THz doubler device is shown in Figure 6. The curvature to the beam leads and the diode fingers occurs as a result of their non-planar fabrication, rather than strain. Only the membrane portion of the diode circuit is shown in the figure.
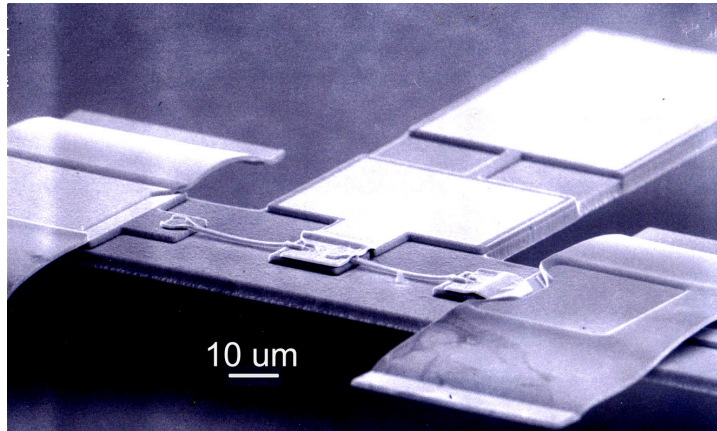

Figure 6. 1.5 THz doubler SEM photo showing the same region as in Figure 4.

1.5 THz Doubler Tests

No solid state driver source is presently available near 750 GHz with enough power to drive this doubler. A preliminary test was needed to determine the feasibility of such a doubler and the required drive level. The results of this test would be used to develop the driver. Tests were performed in the Submillimeter Technology Lab of the Univ. of Mass Lowell, using formic acid laser lines at 692, 716 and 761 GHz.   Typical output power is 5 -10 mW in all three lines. The laser was focused using a teflon lens into the input horn. The coupling to the horn was relatively poor, because the laser focal spot was somewhat larger than the horn. In order to determine the effective input power, the power was measured using a similar horn on the input to a broadband waveguide calorimeter [2]. The same calorimeter was used with a smaller conical horn to couple to the output waveguide.

In order to monitor the input power, which would very slowly drift during the tests, and to determine the power with the beam attenuated, the laser beam was sampled with a mylar beamsplitter.   The sample was measured with one calorimeter having a horn matching that on the doubler input, while the output power was measured with a second calorimeter of the same type.

Three doubler chips from two wafers were tested in the same block. One had a peculiar IV curve, and gave very low efficiency ~0.1%. Two other devices from the other wafer gave similar good results. The maximum output power is 55 μW at 1522 GHz, at an efficiency of 1.0 %. The output power and efficiency vs. input power are shown in Figure 7. The best operation is with a current bias of 0.5-1 mA, while the bias

voltage is always in forward direction. An output power of 40µW was obtained at 1384 GHz, and 25 µW at 1432 GHz. At frequencies other than 761 GHz, the input power was not so well calibrated, but the efficiency at 692, 716 and 761 GHz input is the same within ±1.5 dB.

An important concern is the minimum input power required to drive an HEB mixer. The input power was reduced with attenuators until an indicated output power of 1 µW was seen. The room environment and the power sensor were sufficiently stable to clearly read this low power. The required input power was 0.4 mW for this output, and this power seems quite attainable with a solid state driver consisting of 3 cascaded planar doublers. Thus far a power of 6 mW has been produced at 378 GHz from 2 cascaded doublers operated at room temperature [3] (which should nearly double at 150 K), and a subsequent doubler with an efficiency of 4% seems consistent with available data at higher and lower frequencies.
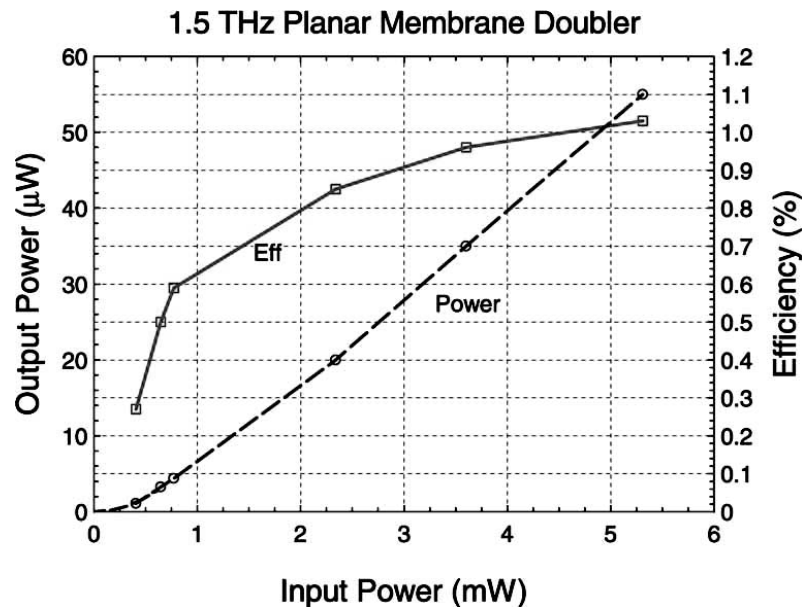

Figure 7. Output power and efficiency vs input power for the doubler at 1522 GHz.

Cryogenic tests

Diode properties improve at lower temperature due to increased carrier mobility. This is observed in all lower frequency multipliers. However, for highly doped THz diodes, we expect much reduced variation in mobility with temperature. A test was needed to determine if any large efficiency benefit would be seen at this high frequency. The doubler survives cooling to 100K, although one device appeared to short out in the bypass capacitor below 200K. The diode IV curve shows a 1.7x increase in slope at 100K, but no change in R_s. A steeper IV should reduce the input power required, even if the efficiency is otherwise unchanged.

A fairly crude test was done with the doubler tested over a LN_2 bath with the laser input at 2.5 mW. At a temperature of 230K the output increased ~10%, but at lower temperature frost began to build up on the input horn, and the output power showed no further increase, with an actual decrease below 180K. A proper test would require a real dewar, but this test suggests that no major efficiency improvement will occur, since the frost build up did not appear to be sufficiently large to produce a very large loss.

Machining

The machining of the block was very easy, considering the small sizes involved. The small features were machined with a 50 μm diameter end mill on a micro-milling machine [4], while the larger features used a 150 μm diameter mill in a second spindle. All critical features used the smaller mill so registration of the tools was not a problem. The one difficult feature was the right angle waveguide, which required plunging a conical horn through a thick block and then meeting this feature with a milled cut from the opposite side. It would be much simpler to machine if this waveguide could be rotated into the same plane as other features, so that both waveguides are split in the E-plane.

The input waveguide can not cross the frame because the presence of the GaAs in the waveguide produces a very large mismatch. However, the frame can be removed. In a test, the frame was glued down at the corners and the frame was then broken in the required area without damage to the membrane. Rotating the input waveguide 90° has no effect on the input match, and the required backshort location fits within the remaining frame. The doubler for 2.5 THz will be machined this way, greatly simplifying this smaller and more difficult part, and also will be tested with a laser.

1 THz Tripler

The 1.0 and 1.2 THz triplers are based on a successful monolithic tripler tested in the 230-330 GHz range [5]. The change is mostly just a scaling in size, but the membrane is significantly thinner than the scaled substrate thickness for the 300 GHz version. The circuit includes two antiparallel diodes in a loop with nearly optimized second harmonic inductance, having an integrated Si_3N_4 capacitor for DC bias bypass. Beam leads are used for dc and rf grounding, and two radial stubs are used to prevent loss of output power to the input circuit. In this smaller size there is some considerable doubt about the effective dielectric constant for radial stubs on the GaAs membrane which depend on the metal of the block for a ground plane. The design assumed that there would be a 1 μm gap under the GaAs, and the stubs were sized accordingly. Variation in this gap is not too critical, and it is unlikely to exceed 2 μm in the worst case. Surface roughness insures that it will never drop below 0.5 μm. An input waveguide probe was added to the THz models to fully integrate the circuit. Because the input probe dominates

the length of the membrane strip, in order to minimize its length, the input waveguide was reduced to 0.6× normal height. The probe was then tuned for this waveguide height, and the transition worked much the same as for full height. The best transition to full height (for bandwidth of the tripler as a whole) was found to be an abrupt step, a short distance from the probe.

The output waveguide for 1 THz is reduced in height to 25 μm at the circuit, but steps to full height very close by. It is broached (scraped out) with a thin tool on the same NC machine used to make the other features. The backshort position and quality is critical, so the waveguide is cut with an integral backshort. It is not possible with this type of machining to cut a vertical wall, but the tool may be brought out of the metal at a 60° angle. This V shaped backshort works as well as a conventional flat wall but the location must be shifted to produce the same effect. The output waveguide includes an additional section of reduced height to increase the bandwidth. The entire waveguide coupling circuit is in one plane, since in this case the circuit topology permits both waveguides to leave the same side of the frame. The output waveguide continues straight to a diagonal horn, while the input wraps around 180° to the input waveguide flange. These details are shown in Figures 8 and 9.
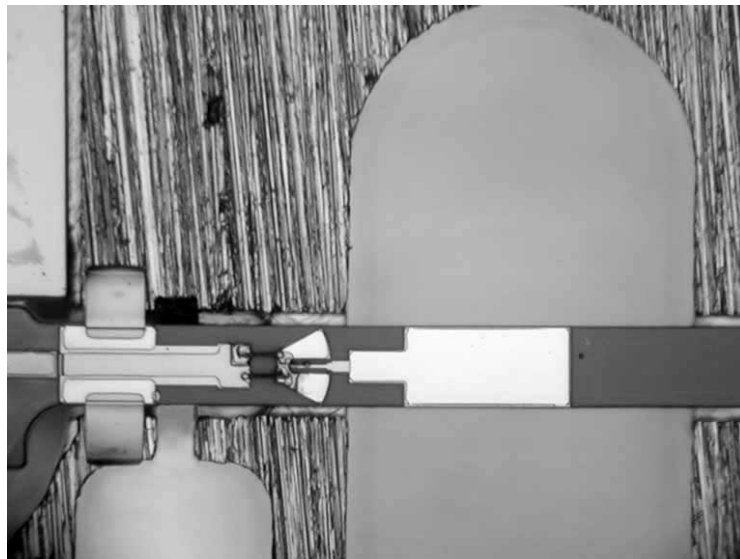

Figure 8. Photograph of the details of the 1 THz tripler, showing the beam leads at far left, output waveguide (next to the beam leads), diodes and radial stubs, and the waveguide probe in the reduced height input waveguide (right).

Figure 9. Overall view of the 1 THz tripler showing the complete frame, bias beam lead on the left, and the wrap-around input waveguide on the right.

Tripler Results

The drive source used in the tests is a Gunn oscillator followed by a MMIC power amplifier producing up to 100 mW output in the 100-110 GHz band, driving a monolithic tripler. The tripler tunes 300-330 GHz with 4-6 mW output power, dropping rapidly at 330 GHz. No source at higher frequency was available, so much of the final tripler's design band corresponding to 320-350 GHz input, could not be tested. Only one device was tested, which gave sufficiently good results that it was not exchanged. The diodes had an odd IV curve, with a very high value for η, but this could be due to the very limited space for ohmic pads, rather than a problem with the diode junctions themselves.

The efficiency is very good, particularly for low available input power, and the low end of the band is nearly at the expected frequency. The highest output power is 80 µW, at 978 GHz, which is comparable to the best seen with a whisker contacted tripler at 800 GHz [6]. Results are shown in Figure 10, with all powers measured with the same waveguide calorimeter as referenced earlier. The typical bias voltage is low, in the range of 0.2 V forward to 0.45 V reverse, with about 0.5 mA bias current. This is not consistent with the optimal varactor mode of operation but the reason for this could be either a diode capacitance below the design value, too little input power, or a limited useful voltage amplitude due to carrier velocity saturation. More tests are needed to determine the cause.

Measurement of the efficiency is not so simple as measuring output power and the input power delivered into a matched load. It is essential to actually measure the power delivered into the load in use, and this requires a directional coupler. A special low-loss

high-directivity WR3 coupler was built for this work [7]. In these tests the true efficiency was measured to be 0.8-1.1% in the 965-980 GHz range, with input powers ~4 mW. No rapid change with input power was noted, although this power should be too low for best efficiency. The input reflected power was 10-20%.

Operation of the full chain, shown in Figure 11, is extremely simple. There are no tuners on the multipliers, and their only adjustment is the bias level. The input frequency is set with Gunn tuner and power with the voltage bias on the power amp. This makes the chain fully compatible with space or remote operation. The interaction between driver multiplier and THz tripler is acceptable, in that any input frequency may be chosen without seeing large output power variations. However, the band tested so far is quite limited relative to that required for FIRST, and full tests are planned when the actual driver chain (consisting of two cascaded doublers) is completed. At low temperature, much higher output power is expected, because the driver tripler is known to show a 57% increase in power [5], and the final tripler should show at least some improvement.
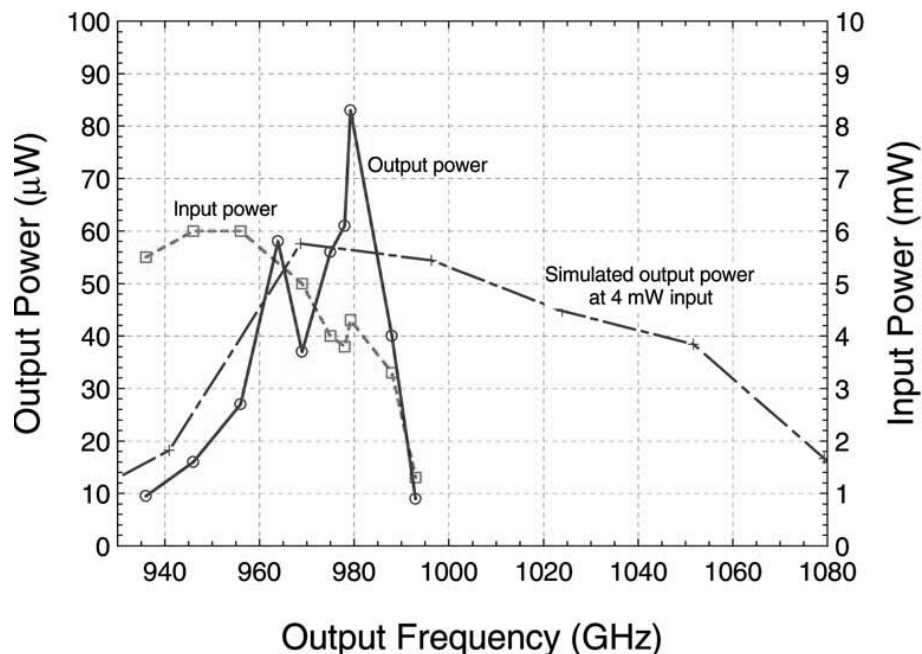

Figure 10. Input power (delivered to a matched load), and output power for the 1 THz tripler, as well as the predicted output power with 4 mW input. Actual input differs due to interactions. No source was available above 330 GHz.
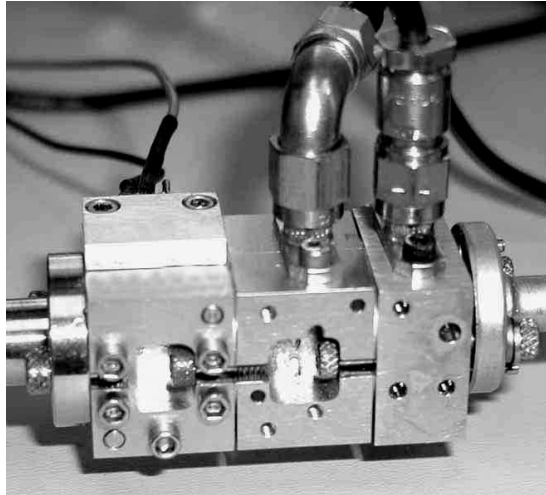
Figure 11. Photo of the complete 1 THz multiplier chain, consisting of (left to right) 100-110 GHz power amp, 320 GHz tripler and 1 THz tripler. The output waveguide on the tripler is a transition from circular to WR10, to match to the power sensor.

Conclusions

The results of this work show that THz monolithic frequency multipliers are quite practical, with excellent performance. A very limited data set indicates that they are also reproducible. These results now make whiskered devices obsolete at all frequencies. At all lower frequencies, planar devices have already shown their superiority, particularly when integrated with most of the multiplier circuitry. The requirement to achieve such good performance is that the circuit must be simple, and there must be an absolute minimum of microstrip or other planar transmission line circuitry. Any such circuitry must be used with careful attention to the losses that will be produced.

The efficiency is high enough to make practical THz solid state sources, which only need to produce a few µW in order to drive SIS or HEB mixers. Cascaded sources are possible with little power ripple vs. frequency, although this may apply only over limited bandwidths. Membrane circuits are quite fragile, yet are quite robust in actual use since they never need to be subjected to significant strain. Machining of the blocks is quick and easy relative to any previous designs, requiring nearly a factor of ten less time than is needed for a whiskered device at the same frequency. Assembly is remarkably easy for such high frequency, and a block may be taken from machined parts to fully functional in a time of ~4 hours.

The large (3 inch) wafer size means that many devices are available, even with a low yield, and a single wafer may contain 10's of different designs, with 100's of each design. This meets the requirements for a major space mission such as FIRST, and also enables a very wide range of other uses. While a wafer run is quite expensive, this

enormous productivity makes circuits in the THz region quite affordable, relative to their whiskered equivalents, and the long term reliability is certain to be much better as well.

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