NASA-CR-199560

NAGW-2430
FINAL
IN-33-CR
OCIT
5586
P. 18

FINAL TECHNICAL REPORT

GRANT NAGW 2430 TO THE UNIVERSITY OF MASSACHUSETTS

PI: Neal R. Erickson
Department of Physics and Astronomy
Lederle 619
Univ. of Mass.
Amherst, MA 01003

Covering the period April 1, 1991 to March 31, 1995

(NASA-CR-199560) [BUILDING AN LO SOURCE AT 1036 GHz FOR A RECEIVER] Final Report, 1 Apr. 1991 - 31 Mar. 1995 (Massachusetts Univ.) 18 p
N96-14075
Unclas
G3/33 0075801

TECHNICAL SUMMARY

The goal of the UMass work on this grant was to build an LO source at 1036 GHz for a receiver which was to be built at JPL. While this source has not been completed, all the designs are finished, and the required parts have either been fabricated or will be completed soon. Thus this goal will be achieved, although the work has taken longer than expected. Some of the design work under this grant was combined with similar work funded by JPL so the total effort is considerably more broad than just the 1036 GHz source.

The 1 THz source will consist of a high power Gunn oscillator at 86 GHz followed by a cascaded pair of planar diode doublers and finally a whisker contacted tripler. All multipliers will use single mode waveguide mounts. This use of single mode waveguide even for the final mount is a departure from the original plan, and reflects the progress that has been made in fabricating small structures. The advantages to the use of waveguide over a quasi-optical approach are that the complete system is much more compact, and much easier to use.

Work that has been accomplished which provides the confidence that we will succeed with this source is in two main areas. The first is a major advance in the state-of-the-art in planar varactor diode multipliers. In Feb. of 1995, a new batch of planar diodes was fabricated in the Semiconductor Device Lab at UVa for use in a doubler designed at UMass. The planar diodes are an array of four diodes on a single chip, intended for high output power at 160 GHz, and previous batches had given encouraging although variable results. This latest batch of diodes was by far the best, and achieved the highest efficiency yet measured with any diodes at a comparable frequency, and did this at the highest available input power. The output power was 58 mW with an input power of 145 mW, for an efficiency of 40%. The exact input frequency was 79.5 GHz, but this is not expected to be critical, and previous tests have shown that the doubler can work comparably well up to at least 175 GHz. This doubler is an essential part of the 1036 GHz source, and its success puts us in a very good position. This success also dispels a lingering worry that planar diodes were in some way inherently inferior to their whiskered counterparts. The reliability of the doubler is excellent, even at full power. We ran a burn-in test for over 100 hrs without any change in output. This test is long enough to demonstrate that the operating power level is fairly conservative. Mechanically, the doubler is very robust. The next stage in the multiplier chain is a 345 GHz doubler, which has been fabricated and tested at 270 GHz, but so far provides rather low power. Details of this device are provided in the reprint attached. This doubler also uses a planar diode array, but the diodes must have rather different properties from those designed for the 160 GHz doubler. The best set of diodes (also from UVa) tested so far produced an output of 5.5 mW with 40 mW input, but even this performance could not be achieved with other diodes. UVa has just finished a new set of diodes for this doubler using the improved techniques which were so successful in the chips for 160 GHz, and these will be tested soon. It seems likely that an output power of 12 mW will be possible, using the drive from the first stage doubler.

The second major success is the completion and test of a tripler for 800 GHz. This tripler uses a whisker contacted varactor, also fabricated at UVa, and a very novel style of construction, detailed in the attached reprint. While this particular tripler was built for another contract for JPL, its design is nearly identical to that for 1THz except for a scale factor, and so it serves as a prototype. This tripler met all expectations for output power and bandwidth, and has proved to be quite reliable as well. The maximum efficiency of about 2-2.5% compares well to the result of 3.5% efficiency at 485 GHz, using a very similar diode in an older tripler design. The output power of 0.11 mW was limited by the available pump power from the only 270 GHz source working at the time. UVa has now completed a new batch of whiskered varactors intended for use in the 1THz region, and these are expected to work even better. This tripler design has been revised to eliminate minor problems, and scaled in size by a factor of 0.8 to change the operating band to 900-1100 GHz. Improvements in the design make maintaining the needed alignment accuracy easier, and it should be possible to machine the structure to the required accuracy. The machining on the new block will be complete in two months, and the assembly with the diode and whisker should follow in another one to two months. Assuming that the new diodes for the doubler and tripler are a success, we may expect an output power of ~0.15 mW at near 1THz. Work is continuing on the hardware developed under this grant because of ongoing support from JPL.

All this work is considerably behind the original schedule due to a number of factors. One main reason has been that without very good planar varactors from UVa, there seemed to be no way to produce a useful pump source at 345 GHz, and these diodes have just become available. A second reason was that it seemed prudent to wait for the first tests of the 800 GHz tripler before using the same design at even higher frequency, and the fabrication of this block was far behind schedule, with the first results only in Feb. 95. It also turned out that the total amount of labor required to test diodes and design the multiplier blocks was much larger that anticipated, and so required more time.

PATENT INFORMATION

No patents (pending or final) have resulted from this work.

FROM SYMPOSIUM PROCEEDINGS:
FIFTH INTERNATIONAL CONFERENCE ON
SPACE TERAHERTZ TECHNOLOGY, 1994

A Balanced Doubler Using a Planar Diode Array for 270 GHz

N.R. Erickson and J. Tuovinen
Five College Radio Astronomy Observatory
Dept. of Physics and Astronomy
University of Massachusetts
Amherst, MA 01003

and

B.J. Rizzi and T.W. Crowe
Semiconductor Device Laboratory
Dept. of Electrical Engineering
University of Virginia
Charlottesville, VA 22903

ABSTRACT

A balanced doubler for 270 GHz has been built using a planar array of four varactor diodes. The maximum output power is 5.5 mW, with 45 mW input, corresponding to an efficiency of 12%. Much higher efficiencies should be possible given the measured device parameters, but circuit or device parasitic losses appear to be a limitation at present.

INTRODUCTION

In the frequency range above 100 GHz, frequency multipliers can achieve high conversion efficiency at low input power, but tend to saturate at a rather low output power. The saturation mechanism is believed to be due to the limited carrier velocity in the GaAs epitaxial layer [1], which leads to a maximum displacement current in the varactor. Since the current increases with frequency for a given voltage swing, this becomes a major limitation for submillimeter applications.

One of the most attractive solutions to this problem is to use series arrays of diodes, because they allow one to increase both the area and the number of diodes, while they may be treated as a single diode so far as circuit design is concerned. In an array having the same impedance level and total power handling as a single diode, the current density varies inversely with the number of diodes. In work reported previously [2], we were able to use this approach to build a doubler for 160–180 GHz using a four diode array which greatly exceeded the power capability of conventional whiskered diodes. The doubler described in this work, operating with an output frequency of 270 GHz, also uses four planar diodes fabricated on a single chip.

The diodes fabricated for this doubler have excellent parameters (as measured at low frequencies) and have been designed for optimized operation in the circuit. A doubler mount has been designed for their use, and the diodes successfully installed. The output power obtained is comparable to that expected from a pair of whiskered devices at the same frequency. However, the efficiency is much lower, apparently due to some presently unknown loss. While this demonstrates the potential for such arrays, work remains to understand the nature of the loss.

DIODE DESIGN AND CHARACTERIZATION

The doubler circuit used is close to a scaled version of the one reported previously [2]. This circuit is quite simple to fabricate, and the installation of planar diodes in the 170 GHz model was fairly easy. The primary design constraint for the diodes is that the chip must fit into this mount. Diodes for this work were fabricated using the surface channel process [3], and this constrains the geometry to be an array in a straight line. The diode layout is shown in Fig. 1, showing the connections to the doubler mount at three points. The large central pad serves as the ohmic contact for the two central diodes, as well as the output terminal. The ohmic contacts for the end diodes are the two small inner pads. The end pads are sized

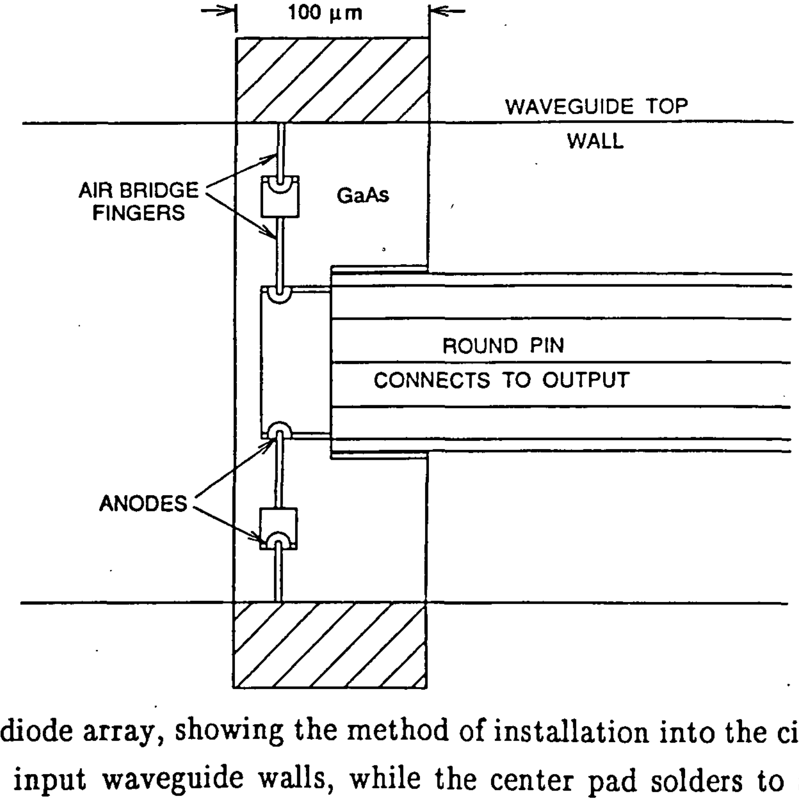

Fig. 1. Planar diode array, showing the method of installation into the circuit. The ends are soldered to the input waveguide walls, while the center pad solders to a pin connecting to the output waveguide. Chip is 370x100x25μm, waveguide is 330μm high.

to permit the chip to be soldered to the top and bottom walls of the waveguide. The diode layout was checked with the Hewlett Packard HFSS program to balance the power to the two diodes of each series pair, as well as to ensure reasonable power coupling to the chip. An effort was made to maximize the circuit inductance within the chip, since all varactors require substantial series inductance to tune out the average junction capacitance.

The series resistance of the parallel combination of the two pairs of diodes (equivalent to the resistance of a single diode) was measured in the doubler mount both at dc and using an HP 8720 network analyzer at 130 MHz [2]. The dc measurements gave a resistance of 6.4 Ω, while the rf measurements were about 1 Ω higher. The capacitance of each junction was measured at 1 MHz using a standard capacitance bridge. The junction capacitance was 16 fF with an additional pad to pad capacitance of 6 fF. The minimum value for the junction capacitance was 6 fF. The available pump power required a total breakdown voltage of only 15 V total for the two series diodes.

DOUBLER MOUNT AND TESTS

The doubler design is electrically equivalent to that in [2], but was scaled and slightly redesigned for use at 270 GHz. A cross section is shown in Fig. 2. All the waveguides were

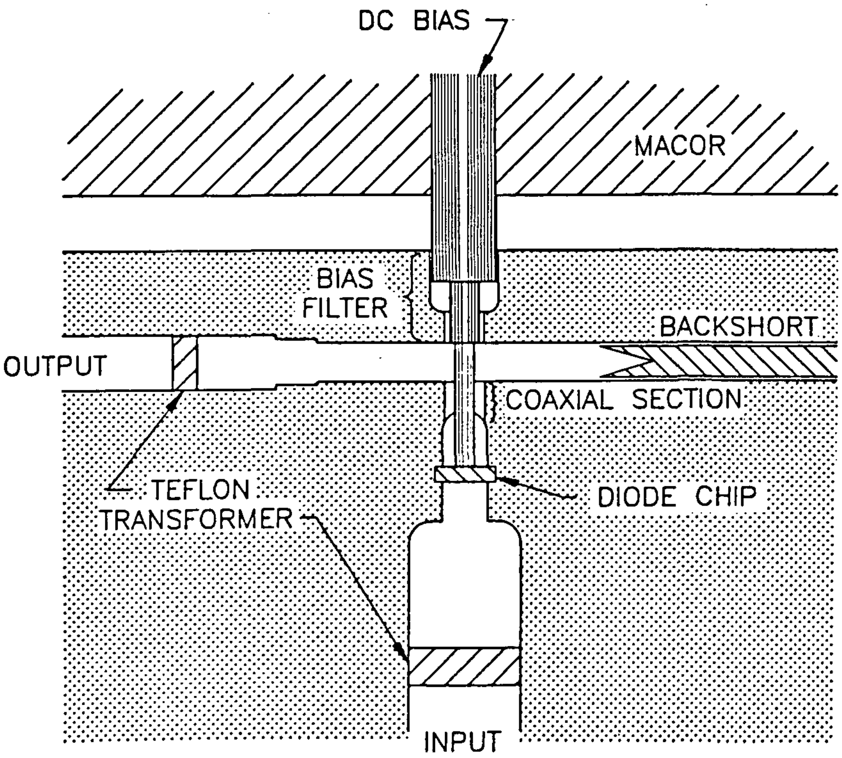

Fig. 2. Cross section through the balanced doubler mount.

milled symmetrically about the center line with the coaxial sections milled with a square outer section. The diode is soldered to the waveguide top and bottom walls as well as to the center pin in one operation, using low temperature indium solder. This operation was difficult with the small chip, but a technique was worked out in which the diode was placed on three thin solder preforms which ensured that the correct amount of solder was used. It is necessary to quickly cool the block after soldering since the solder tends to migrate along the surface of the device and bridge the anodes to the ohmic pads.

All tests were made with a 45 mW Gunn oscillator source tuning 125–145 GHz. The greatest output power was for 135 GHz input. At this frequency, no low loss isolators are available, so the interaction between the oscillator and the highly nonlinear load of the doubler can be severe. This is particularly a problem when neither the source nor the load is matched, as is the case here. To reduce the adverse interaction, a low loss adjustable phase shifter was included in the input circuit. A similar problem exists at the output, where the power sensor used (an Anritsu WR–8 sensor with taper to WR–3) also was poorly matched. The result is that it is difficult to determine the actual input and output powers, and whether the doubler is well matched. The Anritsu sensor was calibrated at both input and output frequencies with the same calorimeter built in WR–12 waveguide [4].

In these tests, the input and output match were optimized using teflon quarter–wave transformers positioned in the waveguide so that the output power was maximized. These transformers can correct a maximum VSWR of:

$$\epsilon(\text{teflon})[\lambda_g/\lambda(\text{air}) \;/\; \lambda_g/\lambda(\text{teflon})]^2 \cong 2.9 \text{ (typically)}.$$

For the input circuit, the strong interaction with the oscillator made it impossible to determine the match obtained, but it was assumed that the maximum power from the oscillator was coupled to the doubler, since the addition of a second transformer was of little benefit. The improvement in power with the addition of the output transformer was only about 25%, meaning that the output match was fairly good. The available power was measured at 45 mW though the phase shifter, by placing a teflon transformer before the power sensor, and varying the phase for maximum power.

The peak output power was 5.5 mW, under bias conditions of 7.8 V and 0.3 mA. The efficiency is 12%, while the theoretical efficiency of the diode (assuming $\gamma = 0.4$, $R_s = 7.4\ \Omega$, $C_j(0) = 16\text{fF}$ for each junction) is 35% at a total input power of 40 mW. While this operation corresponds to the expected varactor mode, only slightly less power (~5 mW) was obtained under very different bias conditions of 2.1 V and 7.4 mA. This is quite surprising since this mode of operation is inherently much less efficient due to the large dissipation of power (15.5 mW) in the bias circuit. This would be the case if the diode had poor capacitance modulation, but this is inconsistent with the low frequency characterization of the diodes. The chip is not expected to show significant saturation at the input power level of 11 mW per junction, but no measurements of output vs. input power have been made. Another possibility is that some unmeasured parasitic loss is present, either in the diode chip or in the doubler mount, and that this loss is relatively more important when the diode is biased in the high Q varactor mode. This type of loss appears to be present on the 160–180 GHz planar diode doubler, and is discussed in ref [5]. Since these diodes are made in a very similar way, a full understanding of the lower frequency doubler should clarify these results.

CONCLUSIONS

A balanced doubler using a planar array of four varactors has been successfully built for 270 GHz. The output power is 5.5 mW at 12% efficiency. This efficiency is considerably lower that is expected from the diodes and work is presently directed at understanding the reason for this discrepancy.

ACKNOWLEDGEMENTS

This work was supported by NASA under grant NAGW–2430, and by JPL under contract 959206.

REFERENCES

[1] E.L. Kollberg, T.J. Tolmunen, M.A. Frerking and J.R. East, "Current Saturation in Submillimeter Wave Varactors," IEEE Trans. Microwave Theory Tech., Vol MTT–40, pp. 831–838, May 1992.

[2] B.J. Rizzi, T.W. Crowe and N.R. Erickson, "A High–Power Millimeter–Wave Frequency Doubler Using a Planar Diode Array," Microwave and Guided Wave Lett., pp. 188–190, June 1993.

[3] W.L. Bishop, T.W. Crowe, R.J. Mattauch and P.H. Ostdiek, "Planar Schottky Barrier Mixer Diodes for Space Applications at Submillimeter Wavelengths," Microwave and Optical Technology Lett., Vol. 3, No. 1, pp. 44–49, Jan. 1991.

[4] B. Vowinkel, "Broad–Band Calorimeter for Precision Measurement of Millimeter– and Submillimeter–Wave Power," IEEE Trans. Instrum. Meas., IM–29, pp. 183–189, 1980.

[5] J. Tuovinen and N.R. Erickson, "Verification of the Finite Element Analysis and Study of Losses of a Planar Diode Doubler," this proceedings.

FROM SYMPOSIUM PROCEEDINGS
SIXTH INTERNATIONAL CONFERENCE
ON SPACE TERAHERTZ TECHNOLOGY,
1995

A Waveguide Tripler for 720-880 GHz

Neal R. Erickson
Department of Physics and Astronomy
University of Massachusetts
Amherst, MA 01003

Jussi Tuovinen
Radio Laboratory
Helsinki University of Technology
Otakaari 5 A, FIN-02150 Espoo, Finland

Abstract

A tripler has been built for the frequency range 720-880 GHz using a novel style of construction intended to minimize the machining difficulties associated with devices at such high frequencies. The performance has been tested with a Gunn oscillator/doubler source producing 4-6.5 mW in the 238-294 GHz range. The maximum output power is $110 \mu W$ with an efficiency of 1.7%. The bandwidth of operation covers the full input range tested, and is consistent with the design expectations, although the center frequency is slightly shifted.

Introduction

Triplers have been built throughout the millimeter range, and well into the submillimeter, using a technique in which waveguides, filters and mechanical supports are machined and assembled into relatively thin wafers, which are then stacked up to form the complete device [1,2,3]. While this method has the advantage that each part is fairly simple, machining tolerances are considerable and the relative alignment of the wafers is critical. It is particularly difficult to measure the outer diameter of the coaxial filter coupling the two waveguides, or the concentricity of the coaxial center pin passing through them. This means that there is no way to ensure that the impedances of the coaxial sections are at the design values. This is a major problem in the fabrication of wideband devices, particularly those designed to have fixed backshort tuning. There are other problems associated with the wafer style design, such as maintaining the required flatness to the rather thin parts, and cutting the diode chip into a nearly round shape so that it will fit the outer conductor shape. All these problems become more severe as the frequency increases, and eventually require a new approach. The tripler described here is an effort to solve these problems, and is largely successful.

While the basic electrical design is the same as previous devices using a stack of wafers, this new structure is built from only two blocks which are split along the E-plane center-line of the input and output waveguides. Most features are machined in a single step, making it easier to maintain the needed alignment. A design constraint was that all features could be machined with conventional tools, without requiring the use of electroforming. While machining of the overall structure is not really easier than for the previous designs, it is far easier to verify dimensions, and to assemble this new design.

Electrical Design

The goal of the microwave design was to produce a tripler which could operate over the 750-900 GHz range, with minimal tuning of the backshorts. Only one tuner in each waveguide is used, and over the midband, they are intended to remain fixed. Such fixed tuned triplers have worked well at lower frequencies where fractional bandwidths of up to 26% may be covered [4]. The electrical design follows closely upon this principal, one critical element of which is the coaxial resonator in the output waveguide which adds the necessary inductance at the input circuit for a wideband match. However, splitting the circuit in the E-plane of the waveguides requires a complete re-evaluation of many of the design features.

Mechanical and electrical constraints required that critical features be split between the halves in the following manner:

- Waveguides are split near the centerline in the E plane for lowest loss. The split line was not exactly on center for the output waveguide because of the asymmetry in the coaxial sections.
- The smallest coaxial sections were machined entirely in one half of the block to avoid problems with the mutual alignment, and to ensure that the most delicate features of the center pin were well protected during assembly.
- The larger coaxial sections partially extend into the mating half of the block in order to maintain coaxial symmetry.
- The center pin of the coaxial resonator (with the whisker attached) is fixed in a channel in the main block with a good electrical contact to ground at the end of the reduced diameter section.
- The diagonal horn was split on the centerline since this horn requires symmetry and this is the only way to machine it.

The inside of the block is shown in Fig.1. The input WR-3 waveguide and output horn are on opposite sides of the block, while the tuners are on the remaining two sides. The coaxial filter uses cross sections having a square outer conductor and a round inner conductor. The center conductor is supported by a ceramic block at one end, with air dielectric throughout the filter sections. The center conductor of the section adjacent to the output waveguide is comprised of the varactor diode chip, which is cut into a square. Since the outer conductor is square, no further shaping is needed. These details are shown in Fig. 2.

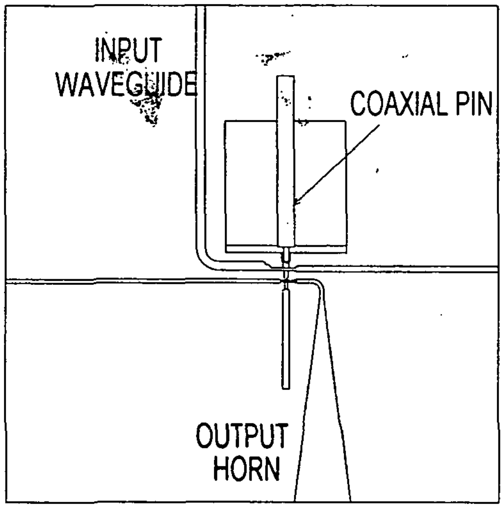

Fig.1. Internal view of the tripler block showing the overall features of the waveguides and horn.

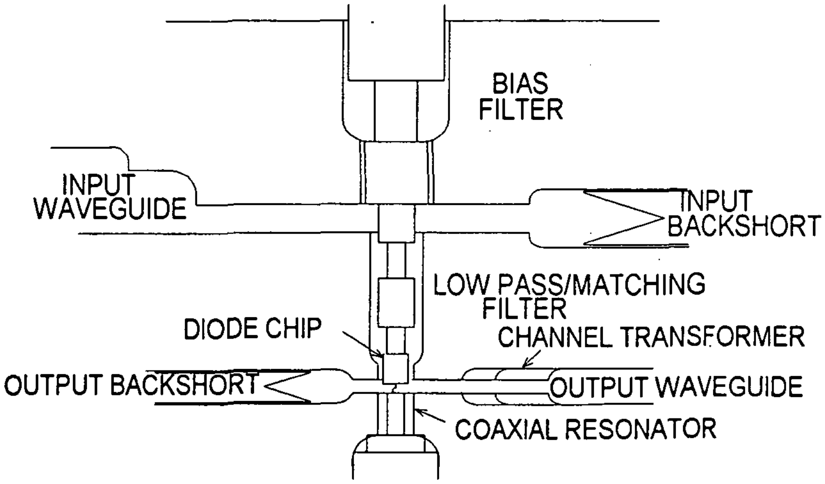

Fig. 2. Details of the waveguides and filters within the tripler, greatly magnified from above.

The design was refined through extensive use of the finite element program HP-High Frequency Structure Simulator (HFSS). This was necessary because of the unconventional cross sections and discontinuity effects involved and eliminated any need for scale modeling except as a final check. The particular problem areas were:

- The output waveguide "channel" transformer, particularly discontinuity capacitances at the steps.

- The off-center mounting of the diode in the output waveguide. This arises because of the near-center waveguide split and the off-center coax split.
- The discontinuity capacitances at the steps in the unconventional coax.
- Higher mode excitation in the coaxial filter at the junction with the output waveguide.
- Expected backshort locations, to position the steps up to the backshort sections.

Details of these areas are covered in the later sections. The individual pieces were designed with a linear circuit simulator (Touchstone), with the behavior of details and verification of the complete circuit provided by HFSS. The final design verification was performed using a scale model. In this model, minor but critical differences were seen relative to the HFSS predictions. To resolve these, the predicted vs. measured behavior were compared using a circuit simulator. This made it clear that a simple modification would correct the problem, involving just an increase in the size of the diode chip. No complete explanation has been found to resolve the source of the difference.

Coax to output waveguide transition

The size of the coaxial line needed to ensure single mode propagation at 900 GHz is too small for accurate fabrication or assembly, particularly with the use of the square coax at the waveguide junction. An alternative approach which has been found to work well is to use a larger cross section, but to ensure that higher modes are not excited. In this case, the maximum possible coax size was desired so HFSS was used to predict the excitation of the next order mode in the coax. Excitation of this waveguide mode is found to be greatest near its mode cutoff and diminishes to a small value at higher frequencies. If this cutoff frequency is set near 690 GHz, it should have little effect on the operation of the tripler in the 780-900 GHz range. This cutoff frequency is achieved with an outer conductor 0.14 mm square and an inner conductor 0.86 mm square. The impedance of this section is 24Ω. In the following sections, the size is enlarged further, since there is little tendency to excite higher modes.

Square outer/round inner coax

The choice of cross section for the coax is purely for ease of machining, and has no circuit advantages. In fact, this cross section tends to have a higher impedance, higher loss and a lower higher mode cutoff than circular coax of similar dimensions. The minimum practical impedance with reasonable clearance is 15Ω. The high impedance sections are 56Ω. Discontinuity effects are very similar to those in comparably sized circular coax.

Waveguide transformers

The waveguides are cut using slitting saws, in order to produce the required reduced height sections. The input waveguide is transformed to full height WR-3 using a conventional $\lambda/4$ step transformer. The reduced height section of the output waveguide is $50\times250\mu m$ and may be cut with a saw, while the full height section is $150\times300\mu m$ and may be machined with an end mill. However, there is no tool available which can machine the transition section using conventional rectangular waveguide. A solution to this problem has been devised in a cross section called channel waveguide [5]. While the original approach was to saw the transition as a long taper, the same cross section may be machined as a step transformer using an end mill. A usual problem with this type of transformer is that the cutoff frequency increases within the transformer by an amount dependent upon the impedance ratio being transformed. This is actually an advantage in the present use because the cutoff helps to suppress the radiation of the second harmonic.

Designing such a transformer with steps is difficult because the impedance of a given cross section may not be chosen independently from its cutoff frequency, and no closed form method of solution exists. In nearly all cases, practical solutions do exist although they may involve more steps than might initially be expected. In this case a two step transformer proved to work well.

Waveguide backshorts

The very low height of the waveguides was expected to cause serious problems with tunable backshorts, particularly in the output waveguide. This problem was expected to be particularly severe if the halves of the waveguide did not line up perfectly. Backshorts will work equally well in waveguides of enlarged cross sections, but their tuning tends to be more critical. However, if the location of the backshort may be predicted in advance, the waveguide may step to greater height at a distance $\lambda_g/4$ away, and so approximate an open circuit at this point. In this case, the backshort tuning becomes much less critical. This approach was used in both waveguides.

Performance

The pump source for all these tests was a Gunn oscillator in the 119-147 GHz range [6] with 35-45 mW output power. This source drives a balanced doubler [3] using a pair of UVa 2T2 whisker contacted varactors ($C_j(0) = 6fF$, $R_s = 15\Omega$). The output power of this source is 4-6.5 mW across the band of interest. This doubler was designed for the 300-370 GHz band, and is far from optimum at lower frequencies. The intended source is a planar diode doubler which has been tested in the correct band [7], but presently has less output than the whiskered doubler. While the optimized power is expected to be >10mW, diodes with the needed performance are still under development.

The tripler uses a UVa 2T8 varactor with $C_j(0) = 4.5fF$, $R_s = 15\Omega$ and $V_b = 10V$. The contact whisker is $3\mu m$ diameter NiAu wire with a total length of $38\mu m$. The tripler is found to operate over the entire range that may be tested with the above source. The optimum bias voltage varies from 0.7-2V (in the reverse direction) with a forward current of $500\mu A$ at the lowest frequencies, decreasing to 10 μA at the highest. This operation is consistent with the designed varactor mode of operation, and is similar to that of devices at lower frequency. Despite the lack of any isolation between the tripler and doubler, the power coupling is good at all frequencies tested, with a fixed spacing between the devices and only backshort tuning. The maximum output power is $110\mu W$ at 790 GHz, where the input power is 6.3 mW, yielding an efficiency of 1.7%. This compares favorably to an efficiency of 3.5% measured for the same diode design in a tripler for 474 GHz [3]. The measured output power across the band is shown in Fig. 3. The variation in the output power is due to a combination of the available input power and the inherent properties of the tripler, so the details of the curve are not significant. The drop in power at both ends of the band is apparently due to the tripler, since the pump source shows no similar trend. At all frequencies, the varactor is underdriven, judging from the bias voltage, which is well below the optimum value of 0.35 V_b typical of most varactors. Thus we may expect the output power to increase with increasing input power, perhaps by a factor of two or more. Some increase in efficiency is also expected. Usually, the high end of the band is most sensitive to low input power, so the greatest gain may be seen here. The measured tuning curve is offset slightly from the design range, but this type of problem is expected with small variations in dimensions.

The performance is not yet optimized, and a variety of minor refinements in the internal geometry are possible. In addition, better varactors are now available from UVa, and will be installed in the near future. The design was intended to require minimal backshort tuning across the band, but the data in Fig. 3 involved peaking at each frequency. It is not certain if true fixed tuned operation is possible with this unit, or if the waveguide steps to full height in the backshort sections are placed correctly. However, this has not proven to be a liability because the backshorts work very smoothly and reliably. There is no tendency for the shorts to lift metal flakes from the waveguide walls as is the usual case, because the shorts do not need to fit tightly to work well.

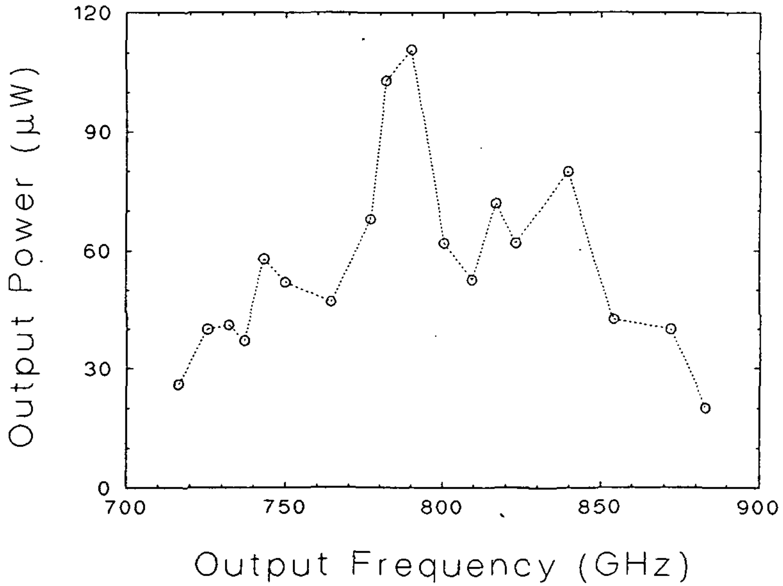

Figure 3. Tripler output power vs. frequency.

Calibration

Accurate power measurements of devices at such high frequencies is quite a challenge because there are few power sensors sensitive enough to detect low power having any reliable calibration. For use in this work, a waveguide calorimeter was constructed which is sensitive enough to detect $1 \mu W$, and which may be accurately calibrated. This calorimeter uses very thin wall stainless steel WR-10 waveguide on the input, with a very low mass absorbing element. It has a VSWR < 1.2:1 in the WR-10 band, and the match improves with increasing frequency, although nothing is known about its behavior well into the submillimeter. The time constant is about 20 sec, which is not a serious problem because the sensor is so stable. The coupling to the tripler output is via a taper from 3.0 mm diameter circular waveguide to WR-10, which is placed against the horn aperture.

Calibration is a combination of measuring the sensor power responsivity using dc heating of a resistor mounted on the sensor, plus a correction for the input waveguide loss (which is frequency dependent). This loss may be determined by adding a second section of waveguide to the input having characteristics identical to those of the internal waveguide (a 35mm length of gold plated SS waveguide), and measuring the decrease in indicated power. It is found that the waveguide attenuation is much higher than expected for the lowest order mode, probably due to a combination of higher than theoretical surface resistivity, and the excitation of many higher modes in the horn coupling power out of the tripler, and the taper into the calorimeter. In this case the internal loss plus that estimated for the waveguide taper is about 2 dB. The actual internal loss may be higher, since the SS waveguide used to estimate the loss has better quality gold plating than the section used within the calorimeter. This method of calibration has been verified at 147 GHz where the corrected power measured with the calorimeter is within 0.1 dB of the power measured with an Anritsu sensor calibrated using other means.

Conclusions

A tripler has been built which tunes from 720-880 GHz with a minimum output power of $25\mu W$ and a typical power of $60\mu W$. The tuning range is very similar to the design value, with an error of only 3% in center frequency. This validates the method of construction, which is intended to permit the design of wide band multipliers in the submillimeter with predictable performance. The efficiency compares favorably with that of a device at much lower frequency using the same varactor diode. This multiplier should provide adequate LO power over nearly the full bandwidth of an SIS receiver.

Acknowledgments

The authors wish to thank Ronna Erickson for her help in assembling the tripler, and Ron Grosslein and Joe Janes for their help in assembling the calorimeter. This work was supported by JPL under contract 959206.

References

[1] Erickson, N.R., "A high efficiency frequency tripler for 230 GHz," Proc. 12th European Microwave Conf. (Helsinki), p. 288, 1982.

[2] Erickson, N.R., "A very low noise single sideband receiver for 200-260 GHz," IEEE Trans. Microwave Theory Tech., vol. 33, p. 1179, 1985.

[3] Erickson, N.R., ”High efficiency submillimeter frequency multipliers,” 1990 IEEE MTT-S Int'l. Microwave Symp., p. 1301.

[4] Erickson, N.R., Goldsmith, P.F., Novak, G., Grosslein, R.M., Viscuso, P.J., Erickson, R.B., and Predmore, C.R., ”A 15 element focal plane array for 100 GHz,” IEEE Trans. Microwave Theory Tech., vol. 40, p. 1, 1992.

[5] Siegel, P.H., Peterson, D.W., and Kerr, A.R. , ”Design and analysis of the channel waveguide transformer,” IEEE Trans. Microwave Theory Tech., vol. 31, p. 473, 1983.

[6] Zybura, M.F. Jones, S.H., Carlstrom, J.E., and Crowley, J.D., ”120-145 GHz stable depletion layer second harmonic transferred electron oscillators,” this conference proceedings.

[7] Erickson, N.R., Tuovinen, J., Rizzi, B.J., and Crowe, T.W., ”A balanced doubler using a planar diode array for 270 GHz,” Proc. Fifth Int'l. Symposium on Space THz Tech. (1994), p. 409.