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.

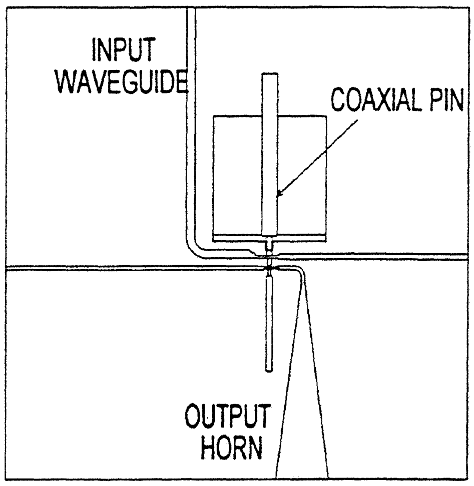

Fig.1. Internal view of the tripler block showing the overall features of the waveguides and horn.

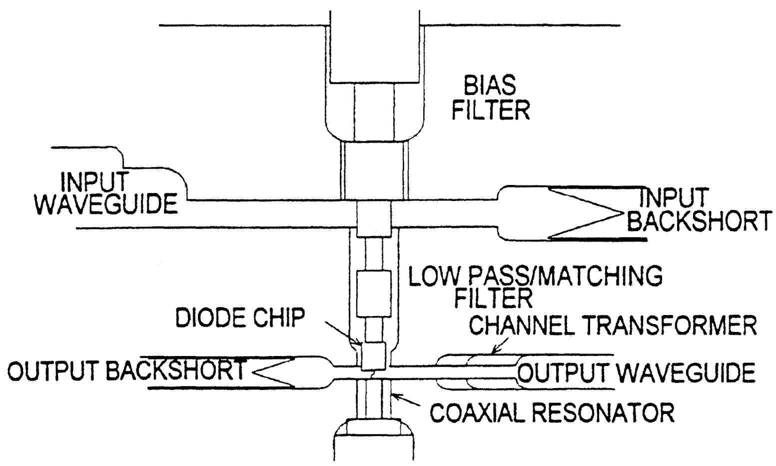

Fig. 2. Details of the waveguides and filters within the tripler, greatly magnified from above.

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.

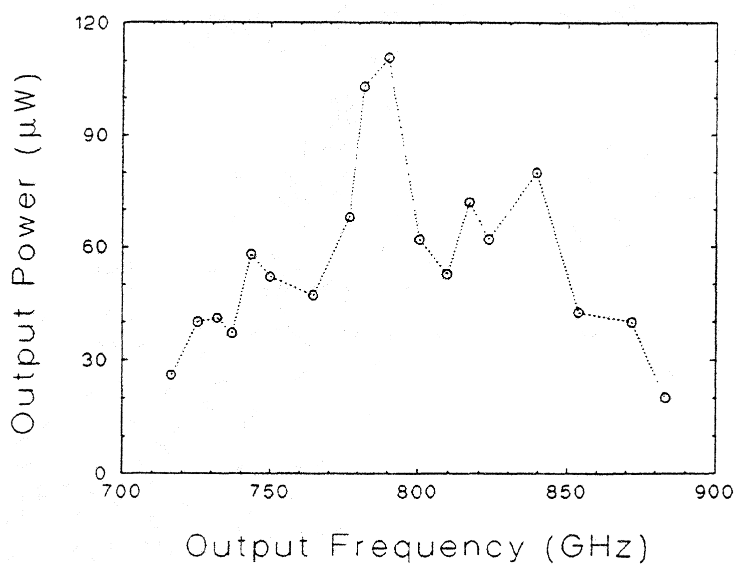

Figure 3. Tripler output power vs. frequency.

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

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