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HIGH EFFICIENCY SUBMILLIMETER FREQUENCY MULTIPLIERS

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ABSTRACT

Solid state sources have been developed for 330 and 500 GHz using cascaded varactor multipliers driven by a Gunn oscillator. The 330 GHz source uses a cascade of two balanced doublers achieving very high efficiency, and produces an output of 4 mW. The 500 GHz source uses a cascade of a balanced doubler and single diode tripler and produces 0.7 mW.

INTRODUCTION

Solid state sources consisting of varactor multipliers pumped by Gunn oscillators are used throughout the millimeter–wave region, but only high order multipliers with low power output have been available in the submillimeter range. In order to produce higher power at these frequencies, it is necessary to use cascaded multipliers. The advantage of cascading is that the first stage may use relatively high capacitance diodes optimized for power handling while the second stage, which runs at low power, may use low capacitance diodes optimized for the highest cutoff frequency. While cascaded multipliers offer a significant advantage over a single higher order stage in terms of power handling, overall efficiency is comparable for optimized designs. However, low order multiplier stages require fewer or no idler circuits at intermediate harmonics in order to achieve optimum results. Newly available varactor diodes combined with novel frequency multiplier designs now make cascading possible with relatively high power in the submillimeter. In this work we describe a doubler for 330 GHz and a tripler for 500 GHz, both pumped in turn by a frequency doubled Gunn oscillator.

FIRST STAGE DOUBLER

This work relies on a new doubler for 160 GHz producing far more power than previously available, which makes cascading practical. Since it is critical to this design, and a similar design is used in the higher frequency doubler, it will be described in detail.

A study of the available mm–wave varactor diodes shows that the highest output power near 160 GHz should be obtained from University of Virginia type 6P4 with $C_j(0) = 21$ fF, $R_s = 10\ \Omega$ and $V_b = 20$ V. This diode has a theoretical optimum pump power of 30 mW, corresponding to the maximum pump power without forward or reverse conduction currents. Experience has shown that this diode may be driven with up to 60 mW input without damage but at lower efficiency.

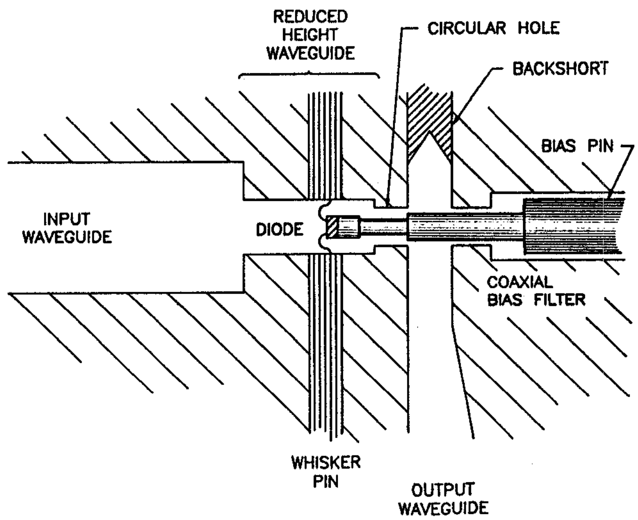

Fig. 1. Internal details of balanced doubler used at 160 GHz. The 330 GHz doubler is similar. Both waveguide cross sections are shown in the E plane.

The doubler developed for this work utilizes a two diode balanced construction which doubles the input power handling and also has the advantage that no filter structures are needed to separate the input and output. This design is much simpler than using power splitters and combiners to add together two independent doublers (1). Lower frequency versions of this design have achieved very high efficiencies (48% at 94 GHz output) so it appeared to be a good choice for higher frequency use. The diodes are in series across the input waveguide and are parallel coupled via a probe into the output waveguide. A cross section of this doubler is shown in Fig. 1. Both varactor diodes are actually on the same 0.25 mm square chip, which is contacted on two anodes.

The input circuit is a simple shunt of the two back to back series diodes across the reduced height waveguide, which ends in a shorted wall. The bias pin has little effect at the input frequency except to lower the guide impedance and the cutoff frequency. The output circuit, driven by the two diodes in parallel, is a "strip" transmission line up to the end of the input guide, where it becomes coaxial as it passes through the back wall of the waveguide, and then couples across the output waveguide. The output waveguide circuit may be tuned with a backshort, but the input tuning is fixed.

The several mode transitions and discontinuities involved in the input and output circuits make designing this circuit tedious, and require some scale modeling for best results. In addition, the circuit design suffers from a number of constraints. The input circuit is complicated by the need to suppress the TM_{11} mode at the output frequency, which has the symmetry to be strongly excited in the input waveguide if the height is too great. Thus the reduced height section where the diode is mounted must continue toward the input for a sufficient length to cut off this mode. The output matching is affected by the transmission line length up to the end of the input guide, which must be short enough to allow a reasonable bandwidth at the output. Adjusting the input waveguide width provides one variable which has little effect on the output circuit, and in addition a step in height or an impedance transformer may be used ahead of the mode suppression section to produce a good match. In lower frequency models, a nearly optimal match has been achieved over a bandwidth of ~15% although that was not the goal of this work.

The doubler is fabricated in three pieces. The input waveguide is milled into the first as a pocket, and the output waveguide is milled as a channel into the next, which also holds the bias pin in a ceramic insulator. The third part simply adds length to the input guide to make the block larger. All parts are gold plated after machining. The 0.25 mm square varactor diode is soldered to the end of the bias pin. Contacting an anode in this geometry has proven to be simple since it is possible to view the diode face–on with a high power microscope while contacting. The whisker is made so that rotating the whisker pin will bring it into contact with the diode. Input impedance matching is aided by sliding a quarter wave transformer made of a suitable dielectric in the input waveguide to a point where an optimum match is achieved.

Two Gunn oscillators have been used in these tests, one at 79 GHz and one at 83 GHz. Both are dual diode InP Gunn oscillators producing 110–120 mW output at an essentially fixed frequency. These are about the highest power Gunn sources presently practical at this frequency.

This doubler reaches a peak efficiency of 35% with 35 mW input at 79 GHz. Despite the theoretical predictions the efficiency drops to 32% at the expected optimum drive of 60 mW. This rolloff in efficiency is attributed to heating of the diode junction, which is expected to run at ~50 C above ambient at 30 mW per junction. DC measurements have shown an increase in the diode series resistance as the temperature increases, and thus a reduction in the cutoff frequency. It is difficult to quantify the expected increase in R_s with power, since the thermal resistance of the junction is not well known. Despite this effect, reasonable efficiency is maintained at 120 mW input and an output power of 26 mW is produced with the 79 GHz oscillator. An output of 22 mW is obtained with the 83 GHz pump. The measured output power as a function of input power is shown in Fig. 2 for the 79 GHz input. The measured efficiency vs. input power is shown in Fig. 3, as well as the theoretical curve of efficiency. The theoretical curve is generated from a computer program by Siegel and Kerr (3) which was also used to calculate theoretical embedding impedances in this work. Note that the disagreement can not be resolved by any circuit losses, since this would only lower the efficiency at all values and also increase the optimum pump power (for input losses).

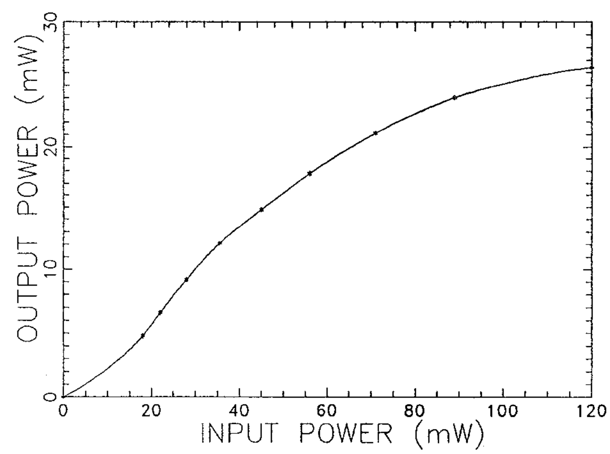

Fig. 2. Balanced doubler output vs. input power, measured at an input frequency of 79 GHz.

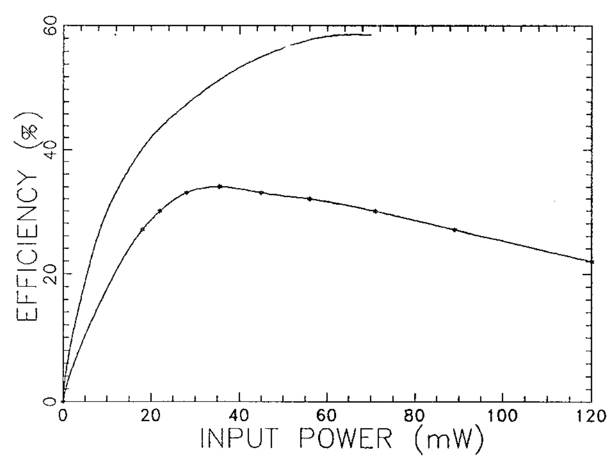

Fig. 3. Balanced doubler measured efficiency vs. input power (lower curve), and theoretical efficiency (upper curve). Theoretical peak efficiency corresponds to maximum (reverse breakdown limited) pump power, and can not be extended beyond this point without knowledge of the behavior of the diode in breakdown.

The very high efficiency is attributed to a very low loss input structure, due to the absence of a filter choke, and to the balancing which suppresses the conversion of power to the third harmonic. Measurements of the output through a high pass filter showed no detectable third harmonic to a level of –35 dBc.

The temperature coefficient may be used to advantage by operating the multiplier at low temperature. By cooling the doubler to 77 K the peak efficiency increases to 40% while the maximum output power is 32 mW. This is the highest efficiency and output power reported at this frequency. This mode of operation is practical in some applications where a cooled receiver is involved.

SUBMILLIMETER DOUBLER

The varactor diodes used in both submillimeter multipliers were provided by the University of Virginia (type 2T2), with parameters $C_j(0) = 6.5$ fF, $R_s = 12\ \Omega$, and $V_b = 8.5$ V. This diode has a theoretical optimum pump power at 160 GHz of 6 mW, either doubling or tripling. For design purposes the diode is modeled as a resistance of 50 Ω in series with a capacitance of 4.1 fF at all frequencies, either doubling or tripling. This is only approximately true, the actual value of the resistance varies from 40 to 65 Ω.

The 330 GHz doubler is essentially a frequency scaled model of the 160 GHz dual diode doubler, with changes to permit a match to different diode parameters and to allow a wider operating bandwidth. This construction is used because of its success in the lower frequency unit and also to reduce the input overdrive. Even at this frequency, the two contacts on a single chip are easy to achieve and the construction is only slightly more complex than a single diode doubler. In this device the output waveguide (reduced height WR–3) was electroformed and the input waveguide (reduced height WR–6) was then machined into the same block, making essentially a one piece construction. The diode chip was cut down to 0.16 mm square, and contacted by two sharpened NiAu wires 6 μm in diameter. This design is believed to be the highest frequency dual diode device of any sort ever built and should be feasible at even higher frequency.

The maximum output power obtained is 4 mW at 332 GHz, which is considerably more than the highest previously available at this frequency using higher order multipliers. If we assume that the input power is 22 mW (the doubler output with the 83 GHz pump), reduced by the 0.4 dB loss of the connecting waveguide, we derive an efficiency of 20%. Note that the overall efficiency of the two doublers is 3.6%, which is about the same as the best single stage quadruplers built at Millitech at this same frequency, but a single stage device is limited to about 1.5 mW output. The varactor bias in these tests was 4–5 V (reverse) with <0.1 mA of forward current.

Powers were measured with a calorimeter (4) in WR–12 waveguide with appropriate tapers to the other bands used. The use of a common standard for all power measurements avoids the calibration errors which frequently occur with the use of different power meters on the input and output. This calorimeter also achieves a very low VSWR and thus results are not influenced by mismatch effects.

SUBMILLIMETER TRIPLER

The tripler for 500 GHz uses a single diode design, similar to that used in a 230 GHz tripler (2). Unfortunately no two diode tripler designs seem practical at this frequency, so the diode should be quite overdriven. This type of design has been refined considerably using theory and modeling to improve the wideband input impedance match to the diode. In addition there are a number of innovations in the electrical/mechanical design to simplify the fabrication and allow the use of split block construction, even at this frequency. One objective of this work was to design a circuit which could be entirely machined, primarily on a CNC mill, without the use of electroformed parts. A cross section of the tripler is shown in Fig. 4. Both waveguides are machined as channels, with one broadwall of each waveguide formed by a third wafer. This wafer contains the coaxial filter joining the two waveguides.

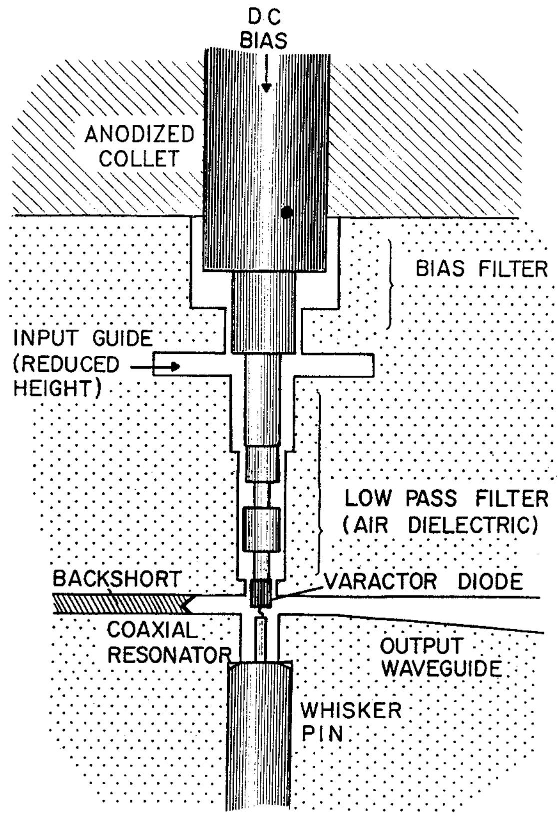

Fig. 4. Cross section of the 500 GHz tripler. The output waveguide taper continues to the conical horn transition.

Modeling was used to help produce an equivalent circuit of the varactor as mounted in the output waveguide and driven by the coaxial filter, based on physically expected circuit elements, plus some empirically determined discontinuity capacitances. Next the transition from the input waveguide to the coaxial filter was modeled to derive the input impedance. A five section filter was then computer optimized to allow an input match from 160 to 173 GHz with no backshort tuning, while simultaneously presenting a short circuit at the second and third harmonics. The coaxial impedances in this filter were allowed to range only from 16 to 54 Ω in order to avoid extreme machining tolerances. Only the final two sections of this filter are small enough to suppress higher modes at the output frequency. The wafer containing this filter is too thin to machine accurately, if a choke of minimum length is used. To add thickness, an extra half wave long section with 40 Ω impedance was added to the input end of the filter, and the design then reoptimized. This addition has very little effect on theoretical performance.

The input match is aided as in a previous design (2) with a coaxial resonator, $\lambda/6$ long at the input frequency, in series with the diode. This resonator adds input inductance without affecting the output match. At the second harmonic idler, the effect is capacitive, which partially cancels the effective inductance of the whisker. Poor contact at the end of this resonator is a potential source of loss, and is reduced in this design by having the shorted end of this pin meet the outer wall at a shoulder where contact can be assured. This makes pressing the whisker pin into the diode less practical as a means of contacting an anode, as is commonly done in such devices. To avoid this problem the position of filter choke was make adjustable by allowing it to slide in a tight fitting anodized aluminum collet, which replaces the previous ceramic support at this location.

To minimize the output waveguide losses, a conical horn was machined directly into the block. This requires a novel transition, based on shapes that are easily machined. The circular to rectangular transition consists of an abrupt step from round to square guide of the same cutoff frequency, in this case 0.53 mm square to 0.62 mm diameter. This introduces no impedance discontinuity, except for the step susceptance which is small. This step is followed by an asymmetric linear taper to reduced height rectangular guide. The final reduced height dimensions are 0.076 mm x 0.42 mm. Making this taper at least 5 λ long keeps the higher mode excitation to a low level causing little perturbation in the feed horn beam patterns. This transition is fabricated by milling the rectangular waveguide taper into one piece of the split block, while the conical horn is bored into the block after the pieces are assembled. The conical horn diameter at the aperture is 1.45 mm.

All parts were machined from brass, and the wafers then lapped to assure perfectly flat surfaces for good mating. Parts were then gold plated. The varactor forms the center conductor of the final low impedance section of the filter choke, and was cut down to the exact diameter needed for the correct impedance. This requires that the diode be soldered to a post smaller than the diode itself. The diode is contacted by an electrosharpened NiAu wire 3.5 μm in diameter, of overall length 70 μm. Contacting backshorts are used for tuning.

The maximum output power is 0.7 mW at 474 GHz when driven with the full output of the doubler, while 0.55 mW is obtained at 498 GHz. This is certainly the highest solid state power output generated at this frequency. Powers are probably underestimated since no mode transition was available from the circular output horn to the WR–12 waveguide of the calorimeter, so these waveguides were simply butted together. An efficiency of ~2% at lower input power is measured at 525 GHz, verifying that operation is over the design band. While designed for fixed tuning, backshorts were optimized at each frequency in these tests. Correcting for connecting guide losses, the best efficiency is 3.0%. Due to the overdriven condition, it is likely that this efficiency would increase at lower input power. The typical tripler bias in these tests was 5–6 V (reverse) with a forward current flow of 0.1 mA, demonstrating that the diode is operating in a true varactor mode. This bias level also implies large reverse breakdown currents since V_b is only 8.5 V.

APPLICATIONS

The doubler output at 330 GHz has been used to drive a harmonic mixer at 660 GHz and plans are to drive yet another doubler at 660 GHz, where an output of 0.1–0.2 mW is expected. The output may prove to be enough LO for a cooled Schottky diode mixer. The tripled power at 500 GHz is quite sufficient for operation of Schottky diode mixers at this frequency, and should be adequate as a pump source for a low power doubler at 1 THz, such as would be used with an SIS mixer.

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