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An Efficient 200–290-GHz Frequency Tripler Incorporating A Novel Stripline Structure

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Abstract—**This paper describes a broadly tuneable frequency tripler which can provide more than 2-mW output power at any frequency between 200 and 290 GHz. It is derived from an earlier narrow-band prototype design, with the major improvements being the use of a new low-pass filter design implemented using a novel suspended substrate stripline structure, an optimized waveguide transformer, and a lower loss contacting output backshort.**

I. Introduction

IN RECENT YEARS, varactor frequency multipliers have become a practical source of local oscillator signals in millimeter wavelength heterodyne receivers [1], [2]. The achievement of optimum performance in a recently constructed multiple-mixer, cryogenic receiver for the 200–350-GHz band [3] necessitated the development of a single frequency tripler which could provide significant output power in the 200–290-GHz frequency range. This paper describes the device developed to meet this requirement. The design of the frequency multiplier was based on an earlier prototype structure [1] which exhibited a significantly narrower operating bandwidth. An improved stripline low-pass filter, an optimized waveguide transformer, and a lower loss contacting backshort represent the major changes made to the original harmonic generator design to enable it to meet the new performance specifications. The resulting device provides a significantly improved output power bandwidth product when compared with previous designs [2], [4].

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II. General Mount Description

The harmonic generator employs a split block construction which has been successfully used in a number of different multiplier designs [5]. The geometry used in this frequency tripler is shown in Fig. 1. Power incident in the full height input waveguide is fed to the varactor diode via a tuneable transition and a seven-section suspended substrate low-pass filter, which passes the pump frequency with low loss, but is cut off for higher harmonics. The

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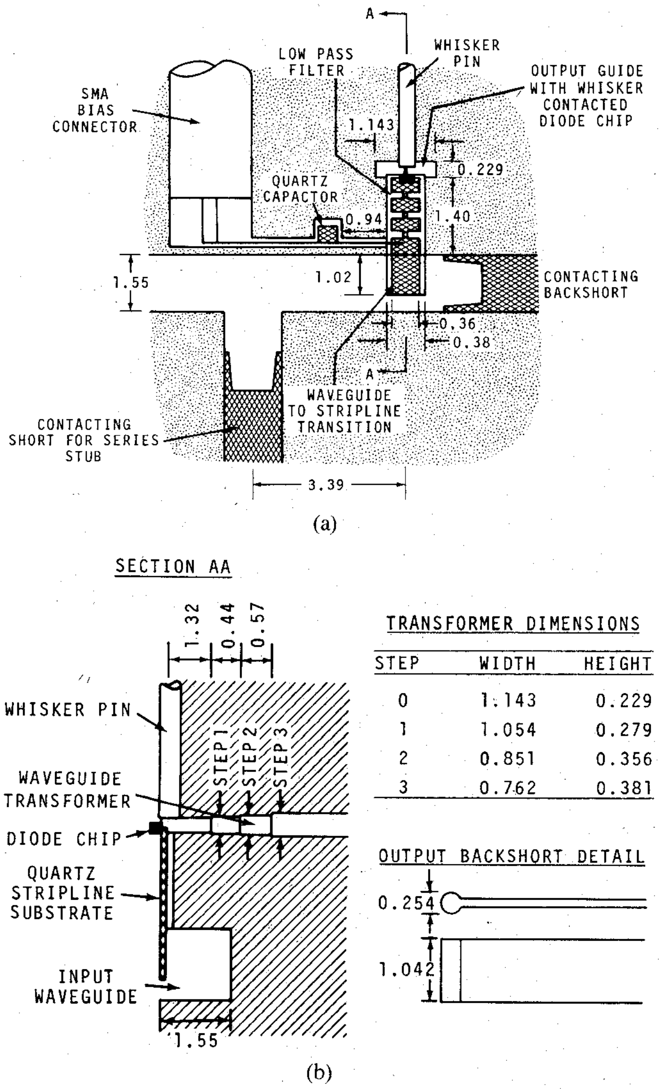

Fig. 1. (a) A view of the tripler block split along the partition between blocks showing, schematically, the input guide, stripline filter, bias circuit, and output waveguide. Dimensions in millimeters. (b) A section through the block detailing the waveguide transformer and diode mounting arrangement. The output backshort configuration is also shown.

varactor chip, a 0.1-mm-sided cube, is mounted on the filter substrate adjacent to the reduced-height output waveguide. One of the many diodes on the chip is contacted and coupled to the output guide with a post-mounted, 0.0125-mm-diam $\times$ 0.15-mm-long phosphor bronze whisker, which has been suitably pointed and prebent. Output tuning is accomplished with the aid of an adjustable backshort in this guide. DC bias is brought to the device via a transmission-line bias filter. The bias circuit comprises a 140-Ω transmission line, consisting of a 0.025-mm-diam gold-wire center conductor bonded at one end to a low impedance section of the low-pass filter and at the other end to a 100-fF quartz dielectric bypass capacitor and enclosed in a rectangular shield machined into the mount. At 95 GHz, the bias line approximates a quarter-wave short-circuited stub, thus minimizing its effect on the performance of the low-pass filter near cutoff.

A quarter-wave, two-section impedance transformer couples the 1.14 $\times$ 0.23-mm reduced-height guide to the 0.76 $\times$ 0.38-mm output guide. Power can flow in the wider guide at the second harmonic, whereas the output guide is cut off at this frequency. The transformer is thus used to implement a reactive second harmonic idler termination by spacing it approximately $\lambda_g/2$ (at the second harmonic wavelength) from the plane of the diode.

The varactor diode is a Schottky-barrier device fabricated by R. Mattauch at the University of Virginia (designated 5M2) with a zero-bias capacitance of 21 fF and a dc-series resistance of 8.5 Ω. The breakdown voltage is 14 V at 1 μA. These devices have a highly nonlinear capacitance versus voltage law which approximates the inverse half-power behavior of the ideal abrupt junction varactor to within about 2 V of the breakdown limit.

The length of the contact whisker is chosen so that its inductance approximately series resonates the average capacitance of the pumped diode at the input frequency. Furthermore, this choice of whisker length theoretically provides, with the aid of the tuning short, a convenient transformation between the diode impedance and the output waveguide impedance at the output frequency. At the pump frequency, the low-pass filter, which is about a half wavelength in total length, transforms the approximately real-valued impedance of the whisker/varactor combination (of the order of 20–30 Ω) to a similar real-valued impedance at the plane of the waveguide to stripline transition. Pump circuit impedance matching is achieved using two adjustable waveguide stubs with sliding contacting shorts. One stub acts as a backshort for the probe-type waveguide to stripline transition and a second as an *E*-plane series stub located $\lambda_g/2$ (at the pump wavelength) towards the source from the plane of the transition. This specific tuning configuration, with 2 degrees of freedom, theoretically facilitates the matching of the guide impedance to a wide range of impedances at the input of the low-pass filter [8]. Mechanical adjustment of these tuners typically enables the input to be matched to the diode impedance with a VSWR of 2:1 or less at any frequency within the operating bandwidth of the WR-12 pump waveguide.

III. Special Features of the New Mount

A. Stripline Structure

The stripline low-pass filter is a seven-section, quasi-lumped-element, 0.2-dB ripple Chebycheff design [6], implemented using alternate high/low impedance stripline sections printed on a crystalline-quartz substrate. The cross section of the stripline channel is unusual (see Fig. 2). It is a modified version of the conventional suspended substrate design [7] which, while maintaining the large ratio between attainable high and low impedances of the usual suspended substrate configuration, allows the channel to be milled in only one of the pair of split blocks.

The impedance and propagation characteristics of the new stripline structure have been investigated both theoretically and practically. Predicted values of line impedance

TABLE I
MEASURED CHARACTERISTIC IMPEDANCE, VELOCITY FACTOR, AND MODING CUTOFF FREQUENCY FOR THE STRIPLINE GEOMETRIES IN FIG. 2 (BASED ON MEASUREMENTS WITH A 62.5 × SCALE MODEL)

C	Characteristic Impedance and v/c for Equivalent Strip Widths (mms)						Moding Cut-Off Frequency (GHz)
	0.0254	0.0508	0.1524	0.2032	0.254	0.3556	
0	106.8/0.642	81.4/0.642	45.2/0.631	36.6/0.625	30.8/0.620	19.9/0.610	310
0.152	114.8/0.675	91.5/0.684	50.3/0.677	40.9/0.670	32.6/0.633	20.9/0.624	335
0.203	120.2/0.690	97.6/0.700	56.0/0.703	44.3/0.696	35.5/0.680	22.0/0.652	350
0.254	124.4/0.699	100.2/0.713	60.3/0.722	48.5/0.716	39.2/0.707	22.6/0.659	358
0.381	136.2/0.702	114.0/0.710	74.3/0.730	60.5/0.724	49.5/0.724	30.1/0.703	266 (with 0.05mm x 0.076mm wall mounting slots for dielectric)

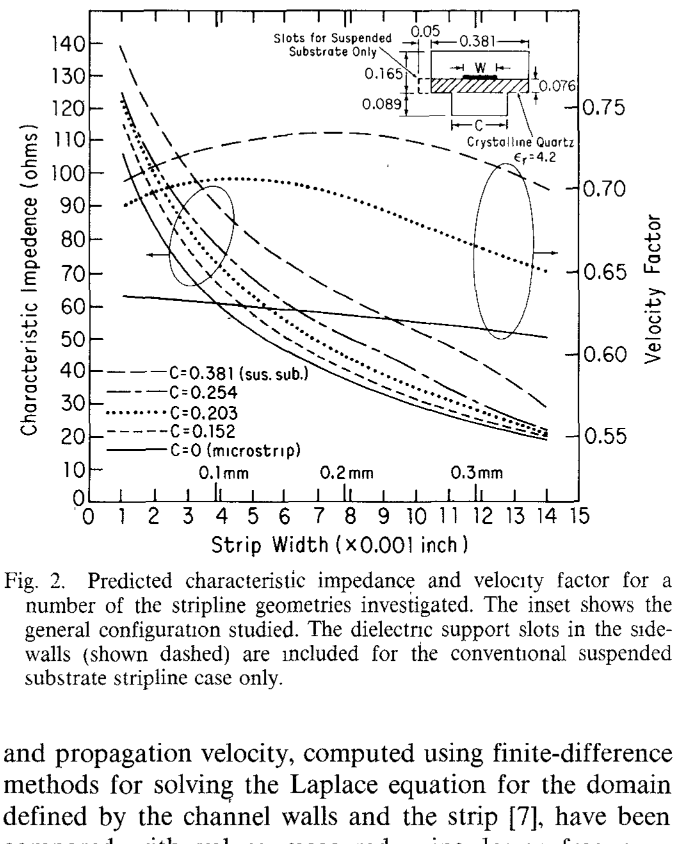

Fig. 2. Predicted characteristic impedance and velocity factor for a number of the stripline geometries investigated. The inset shows the general configuration studied. The dielectric support slots in the sidewalls (shown dashed) are included for the conventional suspended substrate stripline case only.

and propagation velocity, computed using finite-difference methods for solving the Laplace equation for the domain defined by the channel walls and the strip [7], have been compared with values measured using lower frequency scale models of the millimeter-wave structure. Fig. 2 shows predicted characteristic impedance and velocity factor as a function of line width for several different channel geometries. Table I lists some measured values for the line parameters.

Ideally, for broad-band multiplier performance, the low-pass filter in its stopband should present a short circuit to the diode at all the expected second and third harmonic frequencies. In a practical filter, resonances within the components used to realize the device will limit the frequency range over which the input impedance of the filter is a good approximation to a short circuit. The useful stopband width of a lumped element low-pass filter approximated as a cascade of alternate high and low impedance stripline sections is a function of the relative magnitude of the line impedance of the sections. A large impedance difference will in general result in improved stopband performance [6]. The bandwidth is also limited by the onset of higher order modes in the stripline channel. Table I lists the measured first-order moding cutoff frequencies for the geometries investigated here.

The new stripline geometry is clearly an acceptable alternative to either microstrip or conventional suspended substrate designs. With comparable dimensions for the dielectric and channel, the new configuration has a larger impedance range for given strip widths than does microstrip as well as indicating a higher moding frequency. When compared with a suspended substrate structure of similar dimensions, the ratio of attainable high and low impedance values are comparable for similar strip widths. However, in the new geometry, the impedance of the wide strip is lower and is much less sensitive to dimensional tolerances, since in this case the electric field tends to concentrate through the dielectric between the ground plane ledge and the strip. Furthermore, because of the unavoidable presence of the dielectric mounting slots in the suspended substrate technology, the structure described here exhibits a substantially higher moding frequency.

In the design of the filter, by careful choice of channel and substrate dimensions, the moding cutoff frequency can be placed close to or above the upper stopband limit determined by the spurious resonances of the sections. Thus, the useful stopband width may be maximized. Fig. 3 (inset) shows the computer-optimized line and channel dimensions for the filter used in the tripler. In the multiplier mount, the length of the low impedance section to which the varactor diode is mounted is shortened by about 0.025 mm to compensate for the stray capacitance between the diode and the channel walls. The input frequency band is 67 to 97 GHz and the theoretical minimum −20-dB stopband width achieved extends from 130 to 350 GHz, providing a reactive termination for the varactor diode at second, third, and most fourth harmonic frequencies. A computer analysis predicts that the filter should appear as a short circuit to the diode at 265 GHz, and at 200 GHz

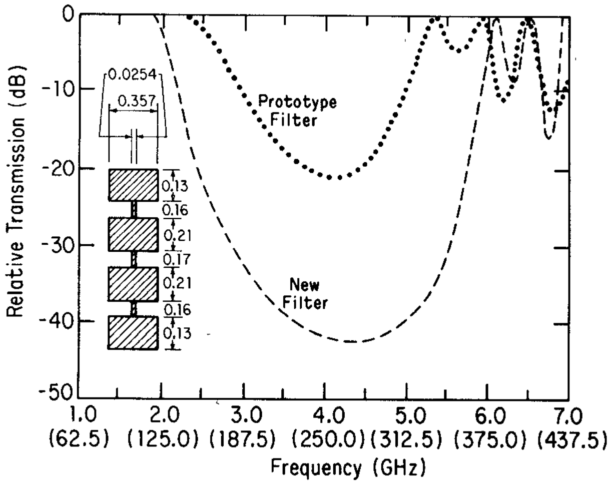

Fig. 3. Measured transmission response of 62.5×scale models of the new filter and the prototype design. The frequencies in brackets are the corresponding millimeter-wave frequencies. The inset shows the metallization pattern dimensions for the millimeter-wave version of the new filter.

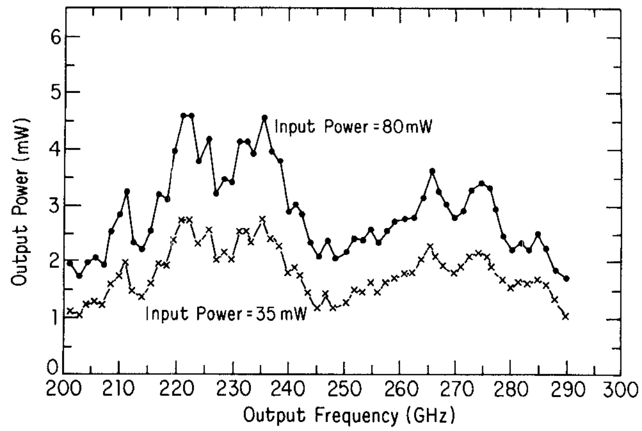

Fig. 4. Output power versus output frequency for the tripler. Bias and tuning were optimized at each measurement frequency. The points have been arbitrarily interconnected with straight-line segments for clarity.

should exhibit a capacitive reactance of 10 Ω. Fig. 3 also shows the measured response of a 62.5×scale model of the new filter compared with the measured response of a scale model of the suspended substrate filter design used in the prototype tripler. There has clearly been a marked improvement in the stopband performance of the filter. For the actual millimeter-wave realization of the new design, a passband insertion loss of less than 0.8 dB and a 3-dB cutoff frequency of 112.5 GHz have been measured using a special fixture.

B. Waveguide Transformer Design

To ensure that the second harmonic is suppressed at the output of the mount for pump frequency below 97 GHz, the dimensions of the output guide were made 0.75 mm× 0.375 mm. The prototype waveguide transformer, from the guide in the vicinity of the diode of dimension 1.143 mm×0.229 mm to that of the output guide, was designed initially using well-known techniques [9]. However, the multiplier block was designed so that transformer sections could be readily interchanged for empirical optimization of the structure. Several transformer half blocks were electroformed with a total ±20-percent variation in the lengths of the intermediate waveguide sections relative to the prototype and with a similar percentage variation in the spacing between the transformer and diode plane (which was nominally 1.46-mm, $\lambda_g/2$ at 167 GHz). Repeated measurements of the mount frequency response with each of the transformer configurations resulted in the choice of the optimum design with dimensions shown in Fig. 1—a design which gives the best compromise termination of the various pump harmonics in the output circuit for good broad-band performance.

C. Output Waveguide Tuning Short

The prototype frequency tripler used a beryllium–copper split-finger-type backshort for output tuning, similar to that used in the input waveguide. This type of contacting backshort is difficult to fabricate for a waveguide with dimensions 1.143 mm×0.229 mm. Even when successfully fabricated, it quickly becomes unreliable and lossy as the very thin fingers lose their elasticity very rapidly. An alternate design was used in the multiplier described here. It consists of a piece of 0.076-mm beryllium–copper shim stock cut to 1.092-mm wide and bent in a loop, as shown in Fig. 1(b), to form a cylindrical compression spring at the end. The uncompressed outside diameter of the cylinder is set to 0.254 mm by wrapping the shim around a 0.102-mm-diam beryllium–copper wire using a special fixture. This type of backshort results in a much more repeatable performance from the multiplier and, because of its lower contact resistance, a significant increase in efficiency when compared with a mount using a split-finger short of similar dimensions.

IV. Multiplier Performance

The performance of the multiplier was measured at 1500-MHz intervals for output frequencies between 201 and 295 GHz. The output power response as a function of output frequency for constant 80-mW pump power (the maximum safe pump level) is shown in Fig. 4. Backshort tuning and dc bias were optimized at each measurement frequency. Typically, the bias conditions for optimum performance were a reverse-bias voltage of about 5 V and a forward current between 0.1 and 0.5 mA. More than 2-mW output power is obtained at any frequency between 201 and 290 GHz corresponding to a minimum efficiency, for 80-mW pump power, of 2.5 percent. Over most of the tuning range, more than 2.5 mW is available with a peak output power of 4.6 mW corresponding to an efficiency of 5.7 percent.

Higher conversion efficiencies may be attained with lower pump power. The maximum efficiency typically occurs for pump powers of about 35 mW. The relationship between pump power and efficiency is illustrated graphically in Fig. 5 for several different operating frequencies. Bias and tuning were adjusted for best performance at each

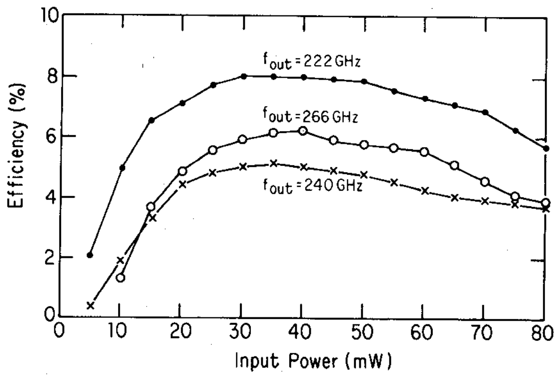

Fig. 5. Output power versus input power for the tripler at three representative measurement frequencies. Bias and tuning were optimized at each measurement power.

pump level. Fig. 4 also shows the output response for a pump level of 35 mW. The minimum efficiency under this condition is 3.1 percent and the maximum efficiency is 8 percent.

V. Conclusion

An efficient frequency tripler with significantly wider tuning bandwidth than previously reported designs has been described. The device provides more than 2-mW output power between 200 to 290 GHz with 80-mW input power. The peak output power obtained is 4.6 mW for frequencies near 225 GHz. The multiplier incorporates a novel stripline low-pass filter design, an empirically optimized waveguide transformer, and an improved contacting output backshort; all factors contribute to the improved performance. Three similar multiplier mounts have been fabricated and tested and all perform as well as the mount described in this report. The tripler is currently being used as an LO source in a multiple-mixer heterodyne receiver for radio-astronomical observations between 200 and 290 GHz.

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