Millimeter-Wave Sideband Generation Using Varactor Phase Modulators

David S. Kurtz, Jeffrey L. Hesler, *Member, IEEE*, Thomas W. Crowe, *Senior Member, IEEE*, and Robert M. Weikle, II, *Member, IEEE*

***Abstract*—A sideband generator based on phase modulation is presented. The sideband generator consists of a Schottky varactor diode mounted in a WR-10 waveguide tuned resonant circuit. A microwave pump signal modulates the phase of the reflection coefficient the circuit presents to an incident millimeter-wave signal. This proof-of-principle circuit has shown a sideband conversion loss of 9 dB and bandwidth of nearly 10% at 80 GHz. These results represent significant improvements over the performance of sideband generators based on resistive mixing in corner-cube mounts.**

***Index Terms*—Millimeter-wave sources, sideband generation, varactor diodes.**

I. INTRODUCTION

OVER the past several years, instrumentation needs in the remote sensing and radio astronomy communities have steadily increased the demand for local oscillator sources operating at millimeter and submillimeter wavelengths [1], [2]. Tunable sources of submillimeter radiation are uncommon. Far-infrared lasers operate at discrete spectral lines with typically no more than 200 MHz of bandwidth and tunable solid-state sources produce meager amounts of power as their operating frequencies approach 1 THz. Sideband generation is a promising method for obtaining a tunable terahertz signal by mixing a fixed-frequency, submillimeter-wave source with a tunable low-frequency oscillator.

Schottky diodes used as resistive mixers for sideband generation have produced useful and tunable radiation at terahertz frequencies but with relatively high conversion loss and limited output power. For example, a whisker-contacted 1T15 diode fabricated at the University of Virginia (UVA) produced 10.5 μW of sideband power at 1.6 THz with 30 dB conversion loss in a corner-cube mount [3]. A 36-element array of planar mixer diodes has given similar results [4]. This letter describes an approach for improving submillimeter-wave sideband generator performance by using Schottky varactor diodes as phase modulators and presents a proof-of-concept demonstration of the method.

II. DESIGN CONSIDERATIONS

A sideband generator is a frequency upconverter with conversion efficiency that depends on the admittance waveform of a pumped nonlinear circuit element. Minimum conversion loss for a resistive diode mixer with all idlers optimally terminated occurs for a pump signal with low pulse-duty ratio [5], [6]. Kelly has shown that a lossless mixer with all idlers terminated in matched loads and conductance driven between a perfect open-circuit and a perfect short-circuit performs best at a 50% duty cycle and yields a minimum conversion loss of 3.92 dB [7]. This case provides a practical limit on sideband generation at millimeter and submillimeter wavelengths where broadband operation is desirable and adequate control of embedding impedances at all the relevant idler frequencies is difficult.

The mixer described by Kelly is essentially a binary phase-shift-keying (BPSK) modulator with tunable phase shift of 0°–180°. Such a phase modulator can be realized with either a varistor or varactor embedded in a resonant circuit [8]. Varactor-based phase shifters, in particular, offer some important advantages for sideband generation including low (ideally, zero) power dissipation [9]. Designing the varactor to resonate with a series inductor when the active region is fully depleted minimizes power dissipation in the diode's series resistance. In addition, the diode's junction capacitance is used as the tuning element that generates sidebands rather than acting as a shunt parasitic.

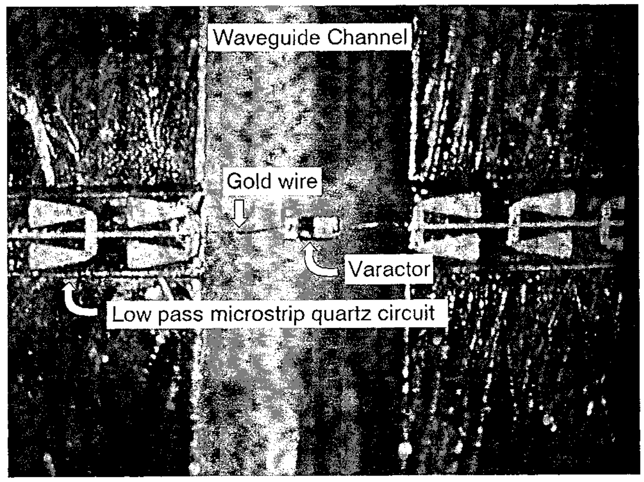

Fig. 1. Photograph of the varactor planar diode chip suspended across the waveguide. Low pass microstrip filters feed the microwave pump signal to the diode.

A photograph of the sideband generator investigated in this work is shown in Fig. 1. The basic circuit consists of a UVA SB3T2 planar varactor diode suspended across a section of

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The authors are with the School of Engineering and Applied Science, University of Virginia, Charlottesville, VA 22903-2442 USA.

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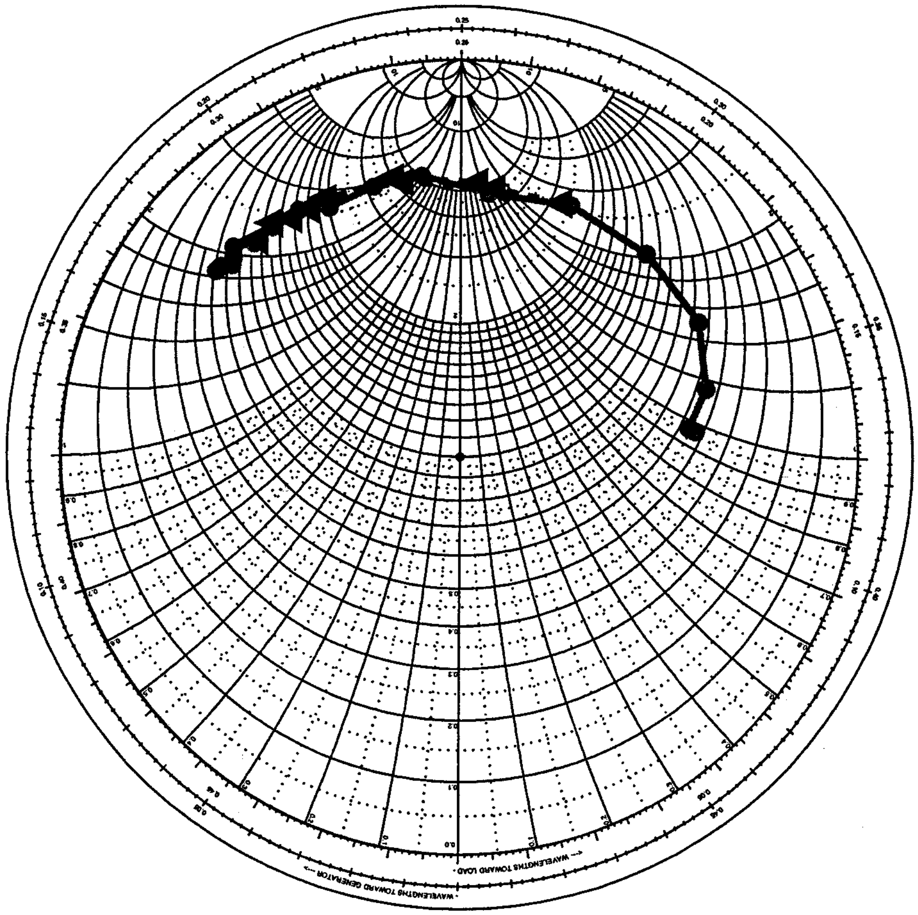

Fig. 2. Return loss (s_{11}) of the sideband generator at 76 GHz as a function of diode bias voltage. The triangles show the return loss as the diode bias is varied from 0.5 V to -7.5 V. The circles show the increase in phase modulation as the varactor is driven slightly into forward conduction.

WR-10 waveguide. These devices, which are typically used for room temperature multipliers, have an anode diameter of 2.5 μm, a nominal zero-bias junction capacitance of 18 fF and an estimated series resistance of 4.5 Ω. The diode is suspended with 0.7 mil diameter gold bonding wire that connects the diode anode and cathode contact pads to microstrip filters on either side of the waveguide. These bond wires provide a series inductance that resonates with the diode junction capacitance at 80 GHz as well as supplying a feed for the microwave pump signal (0–6 GHz). The bond wire inductance and shunt capacitance across the diode chip were initially estimated using the analysis of Eisenhart and Khan [10] and verified with Hewlett Packard's *High Frequency Structure Simulator (HFSS)*. The microstrip filters sit in a shallow cross-channel and consist of a series of shunt radial stubs fabricated on a quartz substrate. These filters were designed with the aid of *HFSS* and produce a short circuit for the 80 GHz signal at the top and bottom walls of the waveguide. A sliding backshort is used for additional impedance tuning.

The phase modulation at 76 GHz produced by the pumped diode is shown in Fig. 2. This data was obtained using a standard function generator to modulate the varactor impedance and measuring the return loss at 76 GHz with an HP8510C millimeter-wave vector network analyzer. The phase of the reflection coefficient is tuned over 70° as the diode bias is varied from 0.5 to -7.5 V. Over this bias range, the return loss is nearly constant at 3.4 dB. Ohmic losses in the waveguide walls, backshort, and diode series resistance are the primary loss mechanisms. The phase modulation (and consequently the sideband conversion efficiency) increases if the pump signal drives the varactor into forward conduction. Fig. 2 shows that the resulting phase modulation is increased to 155° and that the corresponding return loss increases to a maximum of 4.0 dB.

III. Measurements

The sideband generator shown in Fig. 1 was characterized in a WR-10 waveguide test setup consisting of an 80 GHz Gunn diode source, a tunable attenuator, a waveguide switch, and an HP 8565E spectrum analyzer with an external mixer. A diagram of the measurement setup is shown in Fig. 3. The power and frequency of the incident millimeter-wave signal were monitored using the spectrum analyzer and an HP 437B power meter connected to the waveguide switch.

The conversion efficiency from the 80 GHz carrier to the upper and lower sidebands as a function of offset from carrier frequency is shown in Fig. 4. The conversion loss attains a minimum value of 9 dB at 300 MHz and rolls off with in-

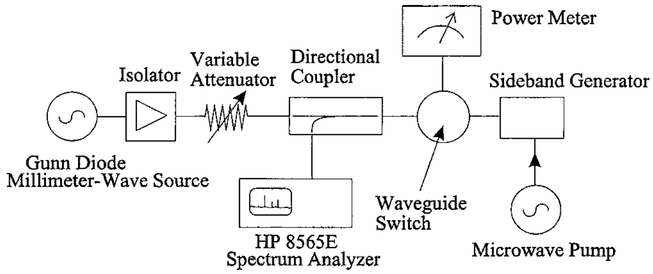

Fig. 3. Test setup for the sideband generator. A waveguide switch connected to a power meter is used to measure the incident power and an HP 8565E spectrum analyzer is used to measure the sideband frequency and power.

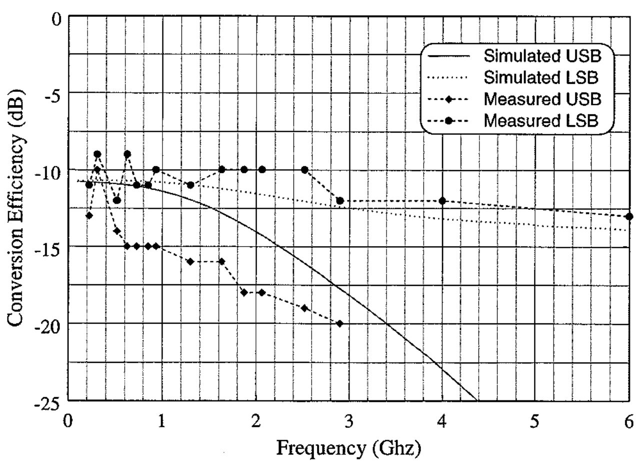

Fig. 4. Sideband generator conversion efficiency at 80 GHz as a function of the offset (pump) frequency. Both the upper and lower sideband frequencies are shown.

creasing offset frequency. For comparison, the predicted performance of the sideband generator is also shown in Fig. 4. Simulations of the sideband generator were carried out using Hewlett Packard's *Microwave Design System (MDS)* software and treating the parasitic inductance and capacitance associated with the diode mount as simple, frequency-independent lumped elements. The values of these parasitics were obtained from an analysis of the waveguide structure at 80 GHz using the method of Eisenhart and Khan [10]. Although this results in a simplified circuit model, the simulations show reasonable agreement with the measured data. The difference in conversion efficiency to the upper and lower sidebands and the roll-off in performance at higher offset frequencies are due primarily to the fixed position of the waveguide backshort.

Fig. 5 shows the conversion loss of the sideband generator as a function of the carrier frequency. For this measurement, the offset (pump signal) frequency is fixed at 300 MHz and the minimum conversion loss occurs at a carrier frequency of 77 GHz. Again, for comparison, the performance predicted by *MDS* is shown and gives reasonable agreement with the measurements.

IV. Discussion

In this letter, we have investigated an alternative method for generating tunable millimeter (or submillimeter-wave) radia-

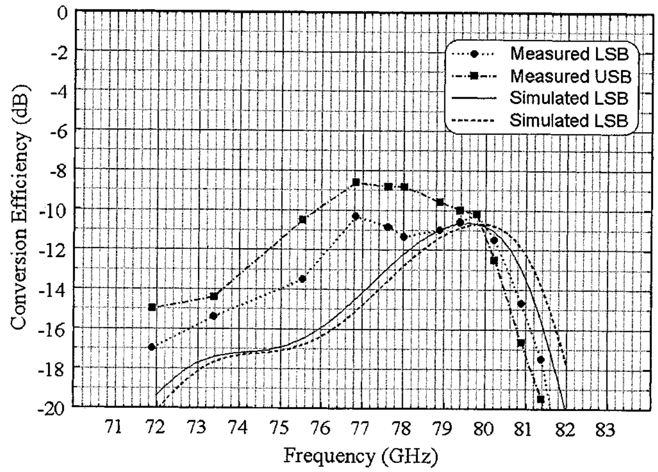

Fig. 5. Conversion efficiency for the upper sideband (USB) and lower sideband (LSB) of the sideband generator as a function of carrier frequency.

tion using a fixed frequency carrier and a pumped varactor. In principle, sideband generation using phase modulators should exhibit improved conversion loss (with a theoretical minimum of 3.92 dB) and enhanced power-handling over their resistive mixer counterparts. The proof-of-principle circuit studied in this letter gave a minimum conversion loss of 9 dB and a 3 dB bandwidth of nearly 10%. It is anticipated that improvements in the performance of this circuit can be obtained with 1) an increase in the capacitance modulation ratio of the varactor and 2) optimization of the diode's pump duty ratio. Although the results obtained in this work are not strictly comparable to those reported by others at terahertz frequencies, the performance of the sideband generator described in this letter represents a significant improvement over that of resistive sideband generators operating in corner-cube mounts.

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