A Distributed Heterostructure Barrier Varactor Frequency Tripler

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***Abstract*—We present a broad-band nonlinear transmission line (NLTL) frequency multiplier at F-band. The multiplier consists of a finline section periodically loaded with 15 heterostructure barrier varactor (HBV) diodes. Tapered slot antennas are used to couple the fundamental signal from a WR-22 rectangular waveguide to the distributed multiplier as well as radiate the output power into free space. The frequency tripler exhibits 10-dBm peak radiated power at 130.5 GHz with more than 10% 3-dB bandwidth and 7% conversion efficiency. The tripler can be used as an inexpensive broad-band solid-state source for millimeter-wave applications.**

***Index Terms*—HBV, NLTL, varactor frequency multiplier.**

I. Introduction

NONLINEAR wave propagation on linear transmission lines periodically loaded with nonlinear devices at microwave and millimeter-wave frequencies have been analyzed and utilized in a range of applications as described in several review articles [1]–[3]. Broad-band harmonic generation from lower frequency sources has been demonstrated using Schottky diodes loading a CPW transmission line [4]. Recently, several authors have investigated the possibility of using heterostructure barrier varactors (HBV's) as a nonlinear element [5]–[8]. The HBV diodes offer several advantages over Schottky diodes. Due to the symmetric capacitance-voltage and asymmetric current-voltage characteristics of the HBV diodes, only odd harmonics of an applied signal are generated. Design of frequency triplers is simplified because no dc bias or even-harmonic terminations are needed [9], [10]. Stacking several barriers in a single device allows for increased power-handling capabilities.

Here, we present a distributed HBV-loaded finline for frequency tripling. The tripler circuit is shown in Fig. 1(a). An input signal at Q-band is first coupled from a WR-22 waveguide to a finline periodically loaded with 15 HBV diodes using a tapered slot. Upon propagation through the nonlinear transmission line (NLTL), the third harmonic (F-band) is generated and radiated into free space from a tapered slot antenna at the output.

II. Design

The four-barrier planar $Al_{0.7}GaAs/GaAs$ HBV diodes (UVA-NRL-1174) [11] are used in this tripler design. At room temperature, the devices exhibit capacitance–voltage and current–voltage characteristics as shown in Fig. 1(b). While the performance of resonant triplers are limited by self-heating of these diodes [11], distributed triplers are less affected because only a fraction of the input power is coupled into each device. The finline also provides a good thermal heat sink for the devices. To facilitate flip-chip mounting of the devices across the line, a finline with 100-μm gap width and 125-Ω characteristic impedance [12] is used.

To eliminate harmonic generation above the third harmonic, the Bragg frequency of the NLTL is set a few percent above the desired output frequency band. Conversion to the third harmonic is most efficient in the band where the fifth harmonic is above the Bragg frequency and the third harmonic is below the Bragg frequency [5].

First, a simplified distributed LC circuit analysis, Fig. 1(c), is performed to determine the device area (diode capacitance) required for an optimized F-band NLTL tripler with a reasonable number of diodes. For sufficient variation in propagation delay with voltage, the per-section transmission-line capacitance C_s is set approximately equal to the average diode capacitance $\overline{C_d}$. A larger ratio of $C_s/\overline{C_d}$ would result in a longer NLTL with a larger number of less capacitive diodes for optimal tripler conversion efficiency. From the chosen capacitance ratio, Bragg frequency (160 GHz), and characteristic impedance of the finline sections (120 Ω), the required average diode capacitance ($\overline{C_d} \sim 11$ fF) can be found. For this tripler, HBV diodes with 57-μm^2 device area, $C_{d,\max} = 26$ fF, $C_{d,\min} = 6.8$ fF, and 1.3-THz dynamic cutoff frequency are chosen. At room temperature, a 16-Ω series resistance can be estimated for these diodes [11].

Finally, the NLTL is simulated using a harmonic balance simulator (HP MDS) with an HBV diode model based on experimental results [11] to further optimize the frequency response over the entire F-band. Optimum tripler performance is simulated with 15 diodes separated by 0.32-mm-long finline sections.

Tapered slot antennas have been investigated by a number of researchers [13], [14]. The broad-band characteristics of these antennas have also been used to develop broad-band finline transitions in rectangular waveguide [12], [14]. The tapered slots used in this tripler are fabricated on a 100-μm-thick crystalline quartz substrate with $\epsilon_r = 4.6$. The length of the tapered slots are 5.0 mm or slightly longer than half-a-wavelength at the lowest frequency of operation. An exponential taper from a 70-μm gap to the full waveguide height (2.8 mm) results in an input impedance of 110 Ω and a simulated 2:1 VSWR

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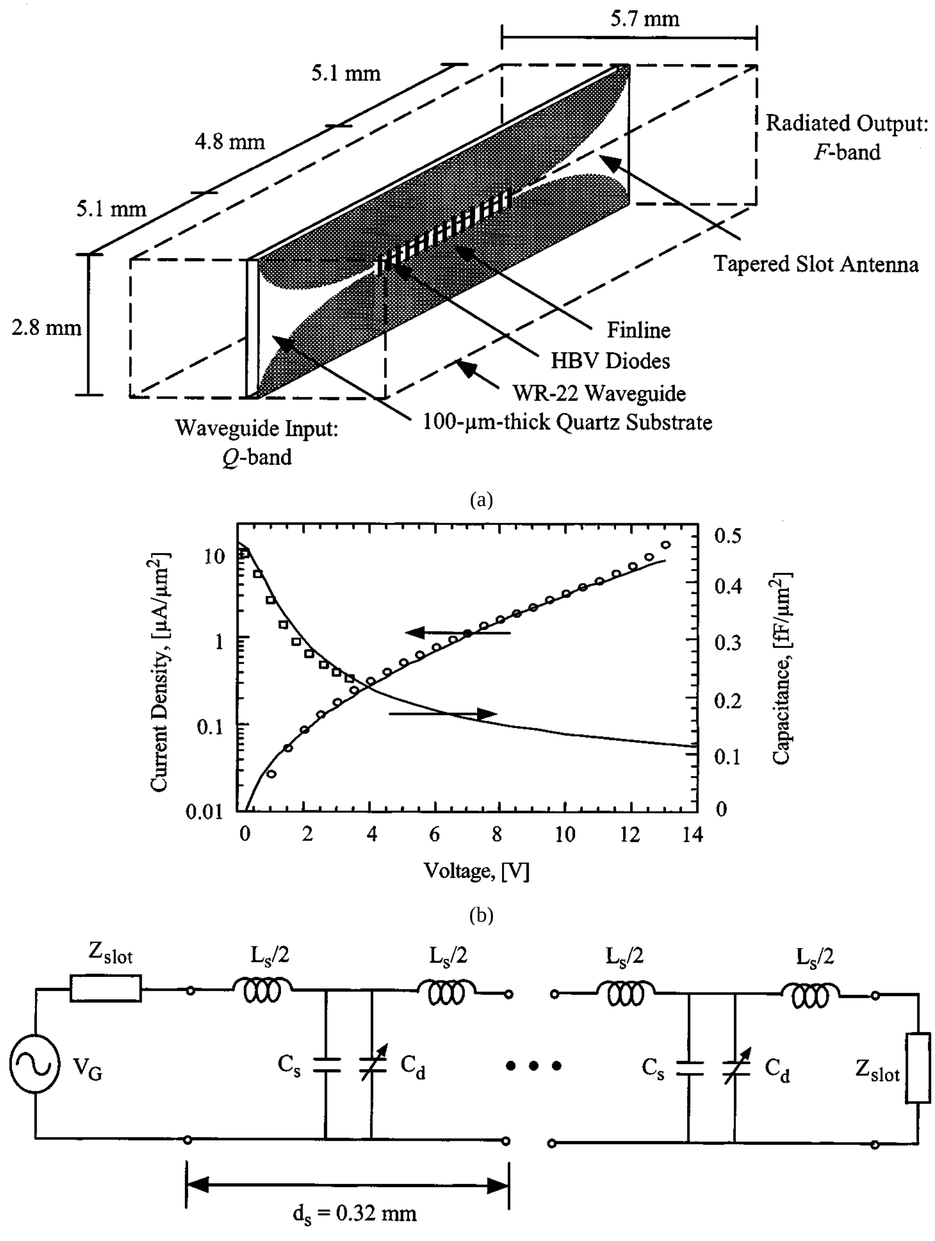

Fig. 1. (a) The nonlinear transmission line frequency tripler consists of two tapered slot antennas connected by a finline loaded with 15 HBV diodes on a 100-μm-thick crystalline quartz substrate. (b) Measured C–V characteristics at room temperature of the four-barrier planar HBV diodes (UVA-NRL-1174) used in the tripler. Due to symmetry, only positive voltages are shown in this figure. (c) An equivalent LC circuit of the NLTL.

from 30 to 150 GHz. The lower input impedance of the tapered slots is chosen to match the impedance of the loaded finline. A 1.5-dB insertion loss was measured for two tapered slot transitions connected by a 5-mm-long 110-Ω finline section at 45 GHz.

III. Experimental Results

To characterize the tripler performance, an F-band horn is connected to an Anritsu power meter (ML 4803A) and located in the far-field of the tapered slot antenna. The waveguide (WR-8) connecting the horn and power sensor has a cut-off frequency above the fundamental frequency (73.8 GHz) and thus allows us to measure the third harmonic. To cover the frequency band of interest, two different klystrons (OKI 40V12 and 47V12) are used to feed the tripler. The measured E- and H-plane radiation patterns of the tapered slot antenna at 135 GHz are shown in Fig. 2. Directivities of 7.8 dB at 112.5 GHz, 10.8 dB at 135 GHz and 12 dB at 144 GHz are estimated from measured radiation patterns. The asymmetry in the radiation patterns can be due to inaccuracies in the measurement setup as well as asymmetry in the antenna due to the quartz substrate. The radiated power from the tapered slot versus frequency is then calculated from the measured *EIRP* as plotted in Fig. 3. In the simulations, a 0.5-dB insertion loss is added at the input and output of the NLTL to account for ohmic losses in the tapered slots. At 130.5 GHz, the measured peak radiated power is 10 dBm with 22-dBm input power at 43.5 GHz. The corresponding conversion efficiency is

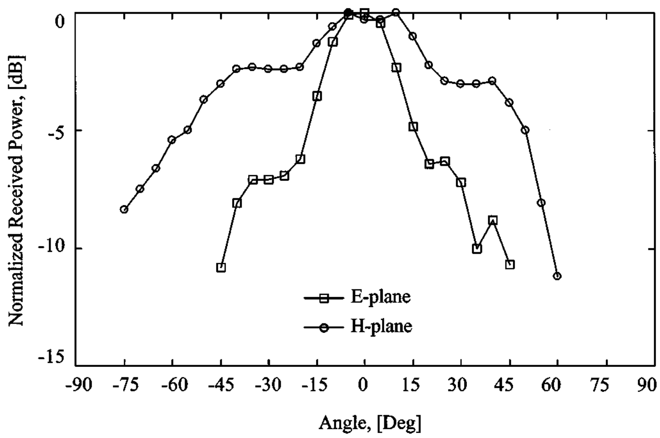

Fig. 2. Measured E- and H-plane radiation patterns of the tapered slot antenna at 135 GHz.

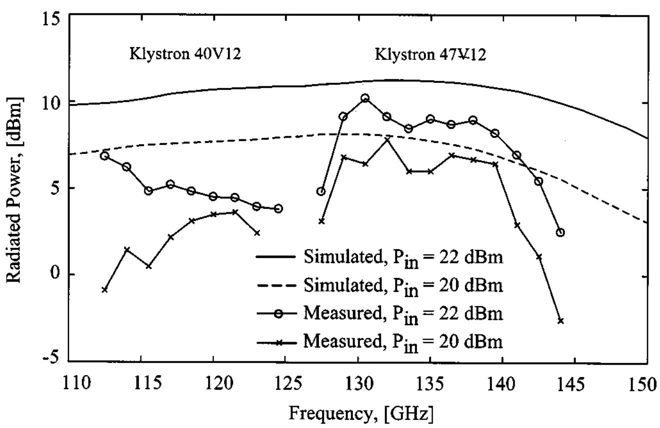

Fig. 3. Measured radiated power from the tapered slot antenna at the third harmonic frequency for input power levels of 20 and 22 dBm. The results from harmonic balance simulations of the NLTL with 0.5-dB insertion loss added at the input and output of the tripler are also included.

7%. The measured 3-dB bandwidth of the tripler is about 10%. However, more than a 20% bandwidth can be seen with less than 6-dB reduction in radiated power. The measured large-signal reflection coefficient at the waveguide input is below -10 dB in the frequency range from 37.5 to 47.5 GHz. The power propagating into the input waveguide at the third harmonic cannot be measured with the experimental setup. However, according to simulations this loss is less than 0.25 mW in the frequency range of interest. The reduced bandwidth of the tripler can be due to inaccuracies in the positioning of the diodes as well as variation in the finline impedance due to excess solder along the finline gap.

IV. Conclusion

This is the first demonstration of a distributed HBV diode loaded nonlinear transmission line for frequency multiplication. The F-band tripler consists of 15 discrete HBV diodes periodically soldered across a finline transmission line with tapered slot couplers at the input and output. The tripler exhibits 10-dBm peak radiated power at 130.5 GHz with more than 10% 3-dB bandwidth. Higher output power and conversion efficiency can be achieved if state-of-the-art HBV diodes [8] with higher breakdown voltages and less leakage currents are used. The multiplier can be used as an inexpensive broad-band solid-state source for millimeter-wave applications.

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