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A Single Barrier Varactor Quintupler at 170 GHz

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Abstract— **InGaAs/InAlAs single-barrier varactor (SBV) diodes are tested as frequency quintuplers. The diodes were tested in a crossed-waveguide structure and provided output frequencies between 148 and 187 GHz. The highest observed flange-to-flange efficiency was 0.78% at an output frequency of 172 GHz. This is nearly four times greater than the best quintupler efficiency obtained for previous SBV varactors made from the GaAs/AlGaAs materials system.**

I. Introduction

Harmonic multiplication of fundamental-frequency oscillators has long been a useful means of generating coherent power at frequencies above 100 GHz. A very effective device for harmonic multiplication has been the varactor diode, particularly the back-biased Schottky-barrier device [1]. Recently, interest has grown in novel varactor diodes having symmetric capacitance-versus-voltage (C-V) characteristic about zero bias. This property suppresses the generation of even harmonics, which simplifies the design of high-harmonic multipliers (e.g., quintuplers) because of the reduction in the number of idler circuits.

This paper concerns the single-barrier varactor (SBV) diode (also known as the quantum-barrier varactor [2], [3]). Theoretical analysis indicates that SBV diodes are good candidates for millimeter and submillimeter wave multipliers with predicted efficiencies as high as 18% at 1000 GHz [4]. In simplest form, the SBV diode consists of two n-type semiconductor cladding layers separated by an electron barrier layer. The doping profile in the cladding layers is perfectly symmetric about the center of the barrier so that the C-V characteristics is symmetric about zero bias. With cladding layers made of GaAs and the barrier of AlGaAs, SBV diodes have been demonstrated as triplers with output between 200 and 300 GHz, yielding a maximum flange-to-flange efficiency of 5% at 222 GHz [3] and 2% 192 GHz [5]. The SBV diode in Ref. 3 was also tested as a quintupler at 310 GHz, yielding a maximum efficiency of 0.2%.

In the present work, we examine SBV diodes made with InGaAs cladding layers and an InAlAs barrier. This combination of materials yields a larger barrier height with less excess conduction current compared to the GaAs/AlGaAs SBV diodes. Two different SBV diodes, one made at MIT Lincoln Laboratory and the other made at the Chalmers University of Technology, were tested in a waveguide quintupler structure with output between 148 and 187 GHz.

II. Multiplier Devices

Both the Lincoln and Chalmers diodes consisted of an $\mathrm{In}_{0.53}\mathrm{Al}_{0.47}\mathrm{As}$ barrier embedded between n-type $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ cladding layers. The epitaxial layers, depicted in Fig. 1, were grown by molecular beam epitaxy on an InP substrate. In order to assist the whisker contacting of mesa diodes, the regions between mesas in the Lincoln diode were filled with $\mathrm{Si}_3\mathrm{N}_4$ and via holes were opened to the SBV mesas by reactive ion etching. The same procedure was carried out on the Chalmers diode with photoresist instead of $\mathrm{Si}_3\mathrm{N}_4$. The Lincoln and Chalmers diodes have areas of about 16 $\mu\mathrm{m}^2$ and 30 $\mu\mathrm{m}^2$, respectively. Fig. 2 shows the measured I-V characteristics of the Lincoln device. Its zero-bias capacitance was 26 fF, as measured with a capacitance bridge at 1 MHz. Beyond ±0.4 V, conduction current prevented capacitance measurements using the bridge. Fig. 3 shows the measured I-V and C-V characteristics of the Chalmers device. The leakage current of the Chalmers diode is considerably higher than that of the Lincoln diode. This is due to the high doping level of the barrier (see Fig. 1) which was applied in order to increase the $C_{\max}/C_{\min}$ ratio. The C-V characteristic together with the series resistance was measured using a vector network analyzer between 50 MHz and 26.5 GHz [6]. The zero bias capacitance was 50 fF and the series resistance was typically between 8 and 9 Ω.

III. Quintupler Mount

The SBV diodes were mounted in a crossed-waveguide quintupler structure in which the input and output waveguides are separated by a low-pass coaxial filter. Fig. 4 shows a schematic diagram of the quintupler structure. Pump radiation between 30 and 38 GHz is coupled in through a half-height WR-22 waveguide and is impedance matched to the coaxial filter using two non-contacting sliding backshorts. The SBV diode is soldered to the far end of the filter pin and is located in the third-harmonic idler cavity. The idler cavity and the output waveguide are coupled through a transition in the waveguide width. The idler cavity is tuned by a non-contacting sliding backshort. The coupling to the output waveguide is controlled by an E-plane tuner with a contacting backshort located just past the waveguide transition. The reduced-height output waveguide tapers linearly to a standard-height WR-4 waveguide. The SBV diode is dc biased (optimum bias 0 V) through a whisker contact across the idler cavity and through the coaxial filter, which is electrically insulated from the waveguide structure by two macor insulation rings.

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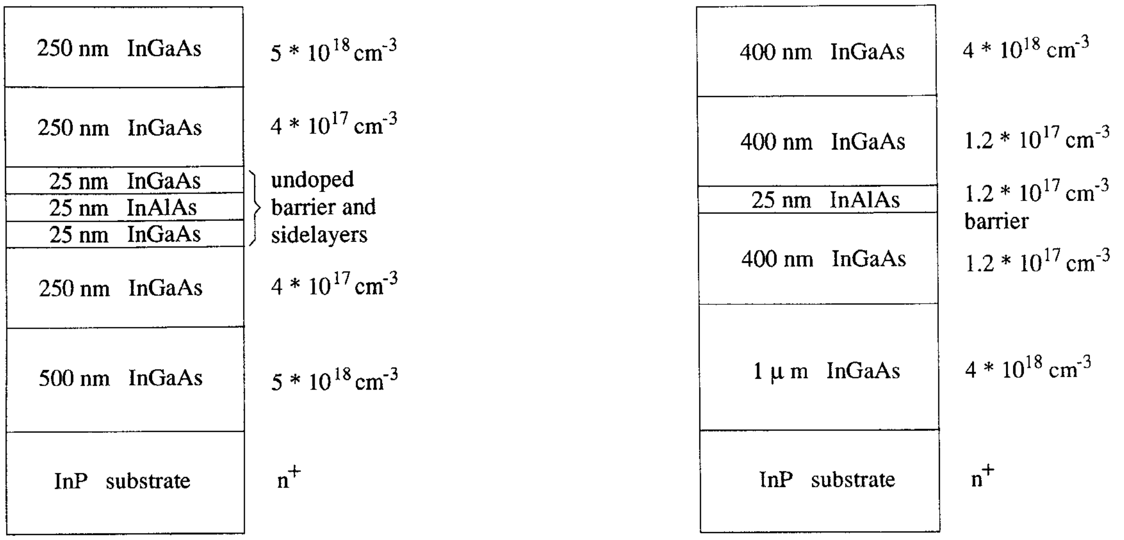


(a) (b)

Fig. 1. Epitaxial layer structure of the (a) Lincoln diode and (b) Chalmers diode.

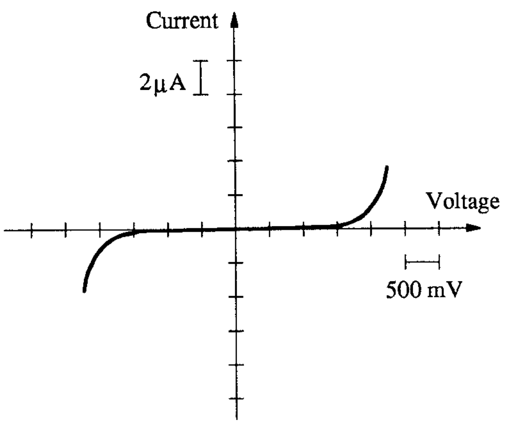
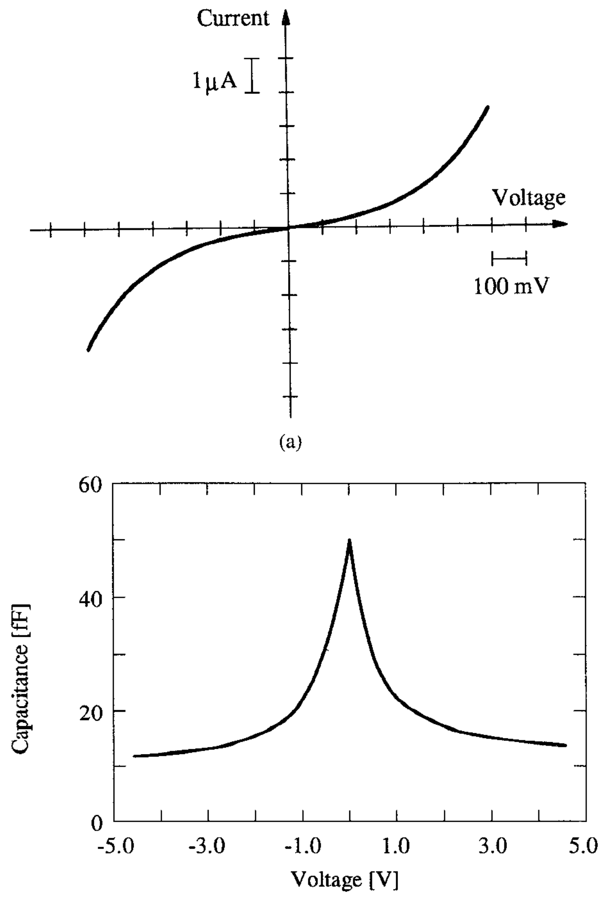


Fig. 2. I-V characteristic of the Lincoln SBV diode.

IV. Experimental Results

The Lincoln diode was tested with 12.7-μm-diameter whiskers having lengths of 305, 254, 216 and 203 μm. The 216-μm-long whisker yielded the best results. Fig. 5 shows the measured flange-to-flange quintupling efficiency versus output frequency at pump power levels of 2.5 and 5.0 mW. The best conversion efficiency was 0.78% with a pump power of 2.5 mW and an output frequency of 172 GHz. Due to saturation, the highest measured output power at 179 GHz was only 29 μW with 6.5 mW of pump power.

The Chalmers diode was tested with whisker lengths of 211 μm and 185 μm. Both gave a maximum efficiency of 0.2% with a pump power of 10 mW.



(a)

(b)

Fig. 3. (a) I-V characteristic and (b) C-V characteristic of the Chalmers SBV diode.

V. Discussion

Although the quintupling efficiency of the Lincoln SBV diode exceeds that of the previous GaAs/AlGaAs SBV quintupler by nearly a factor of four, it falls short of the best results for conventional Schottky-diode varactor quintuplers. For example, a flange-to-flange efficiency of 4.2% was measured from such a device at 168 GHz with 10 mW of pump power [7]. We attribute this shortfall to non-optimal impedance termination and to ohmic losses in our waveguide structure. It is well known that the multiplication efficiency of a varactor diode is critically dependent on the impedance presented at the pump, idler, and output frequencies. It was not possible to

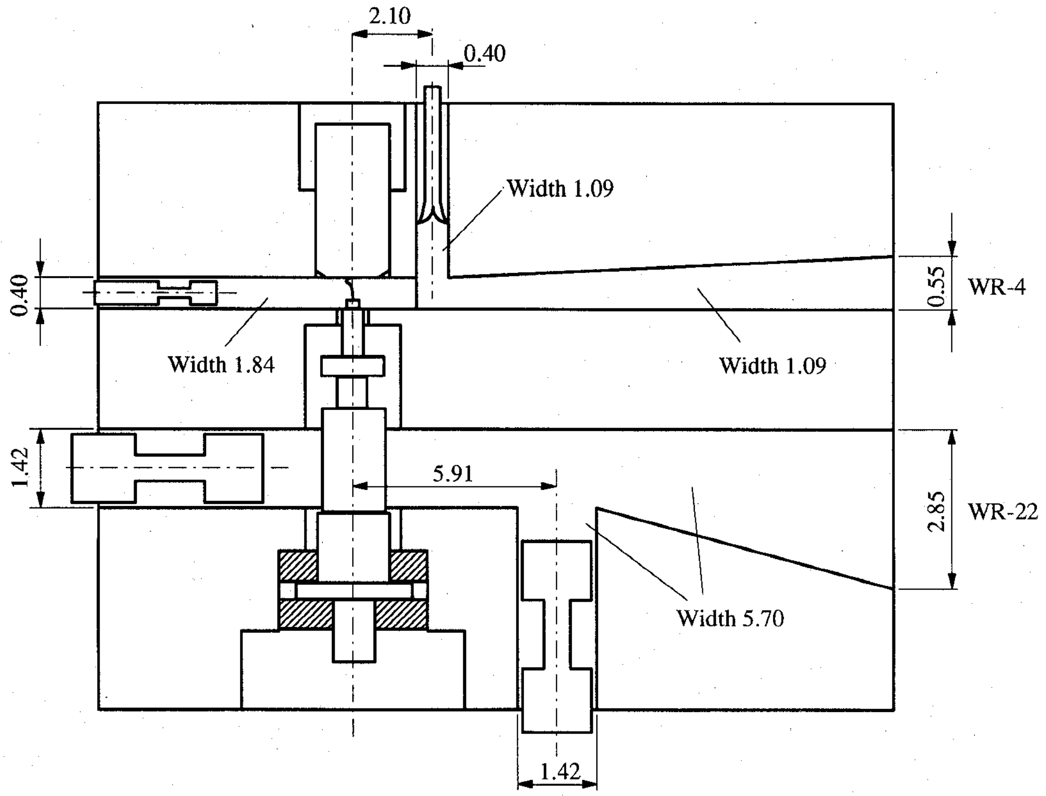


Fig. 4. Schematic diagram of the quintupler cross-waveguide mount.

achieve optimum impedance matching with the present SBV diode and waveguide structure because of the large and variable parasitic resistance of the diodes associated with their voltage-dependent leakage currents. The leakage current was significantly higher in the Chalmers diode than the Lincoln diode due, in part, to its greater area. We believe that this was the primary reason for the lower efficiency of the Chalmers diode.

The leakage resistance of both diodes also contributed to a significant ohmic loss in the circuit. A second ohmic loss term arose from insufficient current paths in the output waveguide between the broad wall and the narrow walls because of a mechanical split along the H-field. The total ohmic losses of the waveguide mount are estimated to reduce the conversion efficience by 2 to 3 dB below the ideal for each diode. The ideal efficiency was computed from a previous theoretical model developed for SBV varactors [4]. In the simulations measured and estimated I-V and C-V curves were used for both diodes. The theoretical results indicate that with perfect impedance matching and in the absence of waveguide losses, the quintupling efficiency of the Lincoln diode would be about 3.5% with 3 mW of pump power and the quintupling efficiency of the Chalmers diode would be about 2.5% and 5% with 5 mW and 20 mW of pump power, respectively. Less power is required for optimum efficiency in the Lincoln diode because of its smaller area.

VI. CONCLUSION

A quintupler with whisker-contacted single-barrier-varactor diodes was tested at output frequencies between 148 and 187 GHz. The highest observed flange-to-flange efficiency was 0.78% at 172 GHz with a pump power of 2.5 mW. This conversion efficiency should improve considerably with better SBV diodes having lower leakage current densities.

Note Added in Revision: With a quintupler mount designed earlier for Schottky varactors [7] the same SBV diodes recently gave better results: Lincoln diode 0.93% at 14 mW at 171.5 GHz and Chalmers diode 0.65% at 22 mW at 172.5 GHz [8].

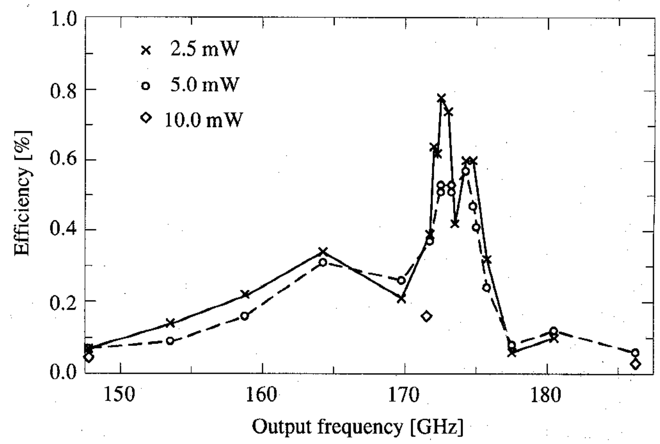


Fig. 5. Measured flange-to-flange quintupling efficiency versus frequency for the Lincoln device (solid line = 2.5 mW; dashed line = 5.0 mW pump power).

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A New Method for Measurement of Complex Permittivity of Liquids Using the Phase Information of Standing Waves

Hanbao Jiang, Mingyi Sun, and Wenjing Chen

Abstract— **A new approach to determine the propagation constant, $\gamma=\alpha+j\beta$, of waves on a transmission line from phase measurements is proposed in this paper. This new method is very suitable for determining small α. Its distinctive feature is that the attenuation constant α of waves on the transmission line is the slope of a linear function of the displacement of a detector. Thus the attenuation constant α can be determined accurately even if it is very small.**

I. INTRODUCTION

Variable-length liquid sample cells have been widely used to measure the complex permittivity of liquids at microwave frequencies. Van Loon *et al.* [1] used the power reflected from a variable-length liquid cell, and Stumper [2] used the power transmitted through a variable-length inclined liquid column to obtain propagation constant. Buckmaster *et al.* [3] recently reported the measurement of the complex permittivity of high-loss liquids by measuring the phase constant and attenuation constant of traveling waves which penetrates a variable-length liquid column. We also made a swept-frequency measurement of the complex permittivity of saline water by using a slotted line [4], in which traveling waves were established.

Thus, except for high-loss liquid conditions in which traveling waves can easily be established, most of the previous works only rely on the amplitude information of standing waves, ignoring the phase information. This causes much difficulty when measuring small α, and requires complicated mathematical processing [5]. The phase variation of a standing wave is highly sensitive to α when it is small. The relation between α and the phase shift on a transmission line is relatively simple. Thus, when α is small, it can be determined more easily and accurately by using phase information than by using amplitude information of a standing wave.

In this paper, we will first discuss the phase characteristics of standing waves on a transmission line in general conditions. Based on the phase information of standing waves, a new method for measuring the complex permittivity of low-loss liquids will be proposed.

Preliminary experiments were performed to prove the new method, and the results show good agreement with the theoretical values and other experimental values. The method provides a new approach to determine the attenuation constant when it is small. The other features of the method include wide-band operation, simple mathematical calculation, and compatibility with the variable-length liquid sample cell method used now.

II. THEORY

On a uniform transmission line, in general a condition, there are standing waves which can be described by

$$V(z\cdot l)=\frac{V_sZ_0}{Z_s+Z_0}\,\frac{e^{-\gamma z}+\rho_Te^{-2\gamma l}e^{\gamma z}}{1-\rho_T\rho_se^{-2\gamma l}} \tag{1}$$

where ρ_T and ρ_s are the complex reflective coefficient of load and source, respectively, Z_o is the characteristic impedance of the transmission line, Z_s is the source impedance, V_s is the voltage of the source, and l is the length of the transmission line.

Two types of standing wave patterns will be used to determine the propagation constant of waves on a transmission line.

A. The Voltage Standing Wave Distribution Between Load End and Source End

In this condition, the amplitude and phase shift of standing waves are [6]

$$|V(d)|=\left|2V_1e^{-\gamma l}\sqrt{\rho_T}\right|\left[\sinh^2(\alpha d+p)+\cos^2(\beta d+q)\right]^{1/2} \tag{2a}$$

$$\varphi(d)=\tan^{-1}\left[\tanh(\alpha d+p)\tan(\beta d+q)\right] \tag{2b}$$

where

$$V_1=\frac{V_sZ_0}{(Z_s+Z_0)(1-\rho_T\rho_se^{-2\gamma l})}$$

d is the distance from load end to the point where the voltage is measured, $z+d=l$, and $p=\ln(|\rho_T|)^{-1/2}, q=-\frac{1}{2}\varphi_r$.

Equations (2a) and (2b) explicitly show that either the amplitude or the phase of a standing wave contains the information of the propagation constant and the load. Fig. 1 shows the phase distributions of standing waves along a transmission line. From Fig. 1, we can see that any phase distribution of waves on a transmission line lies between two lines: one is the straight line, representing a traveling wave; the other is the zigzag line, representing a pure standing wave.

Furthermore, from (2b) and Fig. 1, we can see that the distance D between the two sequential points where the standing wave phase passes through $\pi/2, 3\pi/2\cdots(2n+1)\pi/2$ is exactly equal to $\lambda/2$ of waves on the transmission line. So β is determined by $\beta=\pi/D$. Compared to using the amplitude information of standing waves, the distance between two minimums of the amplitude is not exactly equal to $\lambda/2$ unless the loss of the transmission line can be ignored [5]. From (2b), we can get another form of the equation:

$$L=\alpha d+p=\tanh^{-1}\left[\frac{\tan\varphi(d)}{\tan(\beta d+q)}\right] \tag{3a}$$

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