Quantum-Well Diode Frequency Multipliers: Varistor Case

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Abstract— **Local oscillators for heterodyne receivers at submillimeter wavelengths are typically made using a fundamental source followed by a harmonic frequency multiplier. An investigation of the required circuit embedding conditions for a possible new harmonic generator, the quantum-well resonant-tunneling diode, is summarized. A low-frequency multiplier has been tested that employs the resistive nonlinearity of the device as opposed to the reactive nonlinearity. The results show good agreement between practice and theory.**

I. Introduction

FOR frequency multipliers in the millimeter and submillimeter region, a focus in recent years has been on finding better devices. One candidate has been the high-speed quantum-well resonant-tunneling diode (RTD) described in [1].

The RTD, though theoretically predicted years ago [2], is a relatively recent addition to the semiconductor family. Because of its strong current-voltage (I-V) nonlinearity, it is expected to be useful as a resistive harmonic frequency generator. Further, the I-V symmetry about the origin results in generating only odd harmonics of the applied fundamental signal which allows the required embedding circuit to be much simpler. Previously reported work supported these expectations, with performance close to varactors in that initial effort [1]. Research into using the RTD for this purpose has determined that the harmonic generation at millimeter wavelengths and higher is due primarily to the voltage variable capacitance of the device rather than the resistance [3]. However, in this article experiments are presented to test harmonic generation from the I-V characteristic alone, by operation at very low frequency where the role of the capacitance is negligible.

II. Large Signal Analysis

The crucial step in multiplier analysis is to solve the voltage and current waveforms of the nonlinear device, which is pumped and biased in an arbitrary embedding network. A common solution of this nonlinear problem is to use a type of harmonic balance technique. Time-domain current and voltage solutions are sought which satisfy the diode conditions, and frequency-domain solutions are sought which satisfy the external-circuit equations. In this work, a modified nonlinear analysis program based on Siegel, Kerr, and Hwang [4], was used in order to find the quintupling efficiency of the GaAs–AlAs quantum-well diode. The operation of this device was assumed to be purely resistive. In the analysis, the measured I-V curve shown in Fig. 1 was used.

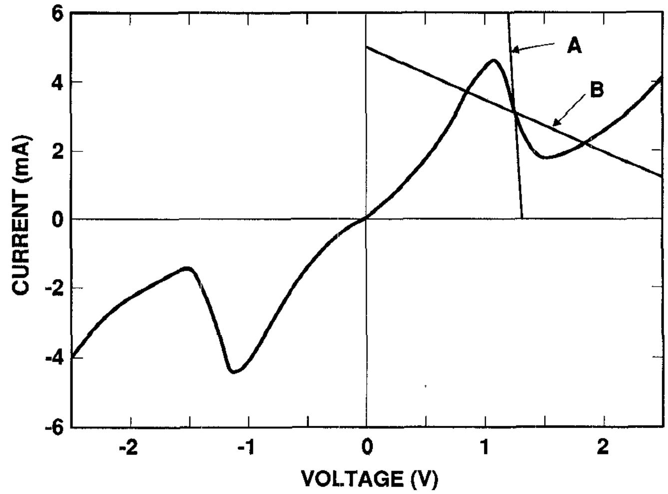

Fig. 1. Measured I-V response curve of the GaAs–AlAs diode. The symmetry about the origin implies that only odd harmonics of the applied fundamental frequency are generated. A unique solution to the operation equation is possible only if the embedding conductance is high, as depicted by load line A. For low-conductance loads, it is not possible to find a unique solution, as depicted by load line B.

The program was modified for the RTD by replacing the I-V characteristics of the Schottky-barrier diode with those of the quantum-well device. However, the I-V characteristic of the quantum-well diode includes the negative-differential-resistance (NDR) region which, in some cases, may affect the convergence of the program. The multiple-reflections algorithm converges to a steady-state solution provided that the conductance slope of the load that the transmission line presents to the device is chosen to be steeper than the maximum differential conductance in the NDR region. This results in a single-valued solution (case A, Fig. 1) as opposed to a triple-valued solution (case B, Fig. 1). Therefore, when the NDR region is very steep, a correct choice for line impedance is only a couple of Ohms. The detailed shape of the NDR-region does not significantly effect the efficiency since the voltage waveform does not spend much time in that region, but rather "jumps" from the resonant current peak to beyond the valley. Hence, it is mainly the peak-to-valley ratio and the nonlinearity beyond the valley, that determine the efficiency.

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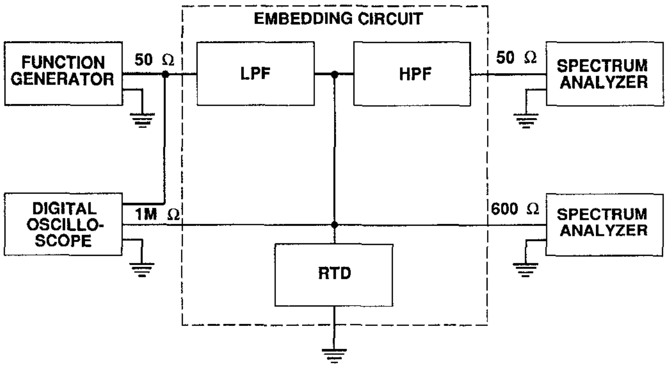

Fig. 2. Calculated versus measured efficiencies for the 3rd through 9th harmonics for a GaAs–AlAs RTD that has been optimally embedded for quintupling. The agreement between calculations and measurements is excellent. The sharp efficiency null for the 5th harmonic occurring at 1.7V. is caused by current phase reversal as explained in the text. – – – – Theory. ——— Measurement.

Theoretical predictions for harmonic generation are shown by the dashed lines in Fig. 2. The case illustrated is for the measured I-V curve, with impedances optimized for quintupling performance. For quintupling, the performance of the GaAs–AlAs diode greatly depends on the third-harmonic idler termination. Since this is a purely resistive case, there is no need for a reactive idler which is essential for a reactive higher order multiplier. If this idler is short-circuited, the highest efficiency is slightly over 1% at a diode input power (Pin) of 3.5–4.5 mW. The efficiency is negligible with input power levels below 2.5 mW. For this particular I-V curve, a nonzero termination at the third harmonic improves the conversion efficiency to the fifth harmonic with low-input power levels. If the third harmonic has a termination of 100–200 Ω, a peak efficiency of around 2.5% is reached with Pin $\approx$ 2.2 mW (about 1.4 V., Fig. 2). In this case, the efficiency curve has a local minimum at or around Pin $\approx$ 3.3 mW (1.7 V, Fig. 2). At this point the fifth harmonic drops to zero due to the current transitioning from in-phase with the voltage to out-of-phase. If input power is further increased, the curve rather closely follows that of the short-circuited idler case.

III. Experimental Verification

An experiment was designed to verify the results of the large signal analysis. Testing at a low frequency was indicated in order to restrict the operation to the resistive mode only, minimizing the effects of the nonlinear capacitance and higher-frequency parasitics. The embedding circuit, depicted functionally within the dashed lines of Fig. 3, consisted of a low-pass filter input section, the RTD and a high-pass filter section. Carefully selected, lumped elements were used to perform the impedance matching and filtering functions. Although the input impedance of the high-pass filter was optimized to the diode for quintupling, other harmonics were present, permitting measurement of their performance at several, though not ideal, impedances.

Using the setup shown in Fig. 3, measurements were made at harmonics of the 10-kHz input frequency, up to 90 kHz, as a function of input and output impedance of the device itself.

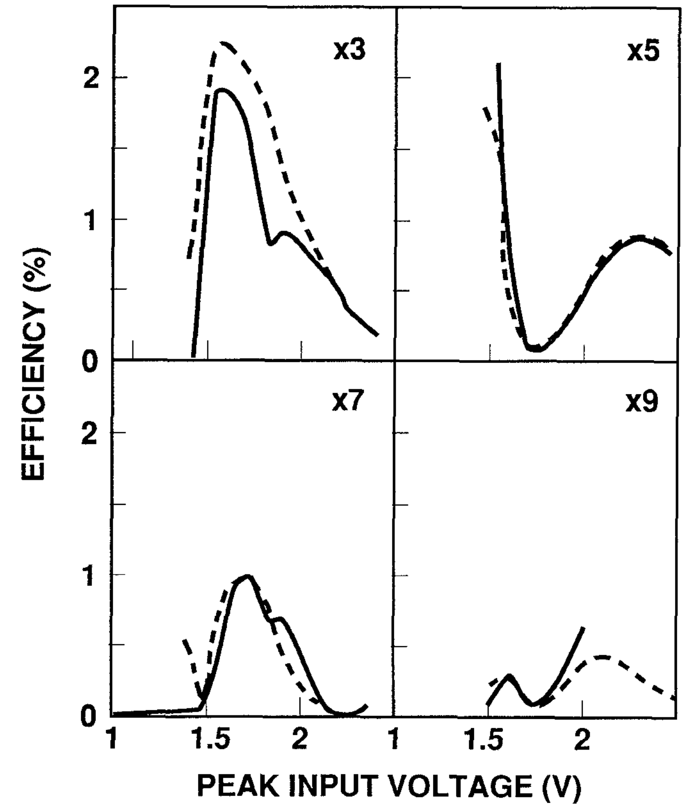

Fig. 3. The measurement setup with the device embedding circuit, containing the input low-pass filter (LPF) the resonant-tunneling-diode (RTD) and the output high-pass filter (HPF), enclosed in dashed lines. For these 10 kHz input frequency measurements, the filters were constructed of lumped elements. The RTD was mounted and contacted in an approximately coaxial structure.

These measurements were of voltage waveforms, at the RTD and at the input filter, and of power, at the RTD and at the output. In addition, in a separate set-up using a small (10 Ω) resistor in the RTD lead, it was possible to measure the current waveform, and its angle with respect to voltage waveform, and then infer measured complex impedance at the device.

The solid line in Fig. 2 summarizes the experimental results obtained at each of the odd harmonic frequencies up to the 9th, as a function of the diode peak input voltage. The theoretical results shown are for the measured embedding impedances of the test setup and the measured GaAs–AlAs diode I-V curve. Because the input voltage waveform "jumps" across the NDR as previously mentioned, we did not observe any oscillatory behavior in the measurements.

The agreement between experiment and theory is excellent, not only for the 3rd harmonic, but also for the 5th, 7th, and 9th harmonics. The results reveal also that, at the 5th and higher harmonics, there exist input power levels at which efficiency drops to zero. As explained previously, this is due to the change of sign for the particular harmonic current component.

IV. Conclusion

This letter describes using the RTD as a resistive multiplier by utilizing its unique I-V response, but the RTD does not compete at millimeter waves with varactors of the same cutoff frequency due to resistive losses. Also, presently fabricated diodes show that above about 100 GHz, the nonlinear capacitance dominates the harmonic frequency generation, while the resistive term degrades the capacitive frequency generation. Devices could be fabricated to minimize the capacitance and sharpen the resonant-tunneling effect for use as a resistive multiplier. Or conversely, fabrication could decrease the resistive effects and improve the nonlinear capacitance for use as a reactive multiplier. Indeed, this last concept led to the single-barrier varactor, which has no resonant well and hence, very low real current, for improved multiplication efficiency [5].

References

[1] P. D. Batelaan and M. A. Frerking, "Quantum well multipliers," *Dig. Twelfth Int. Conf. Infrared and Millimeter Waves*, 1987, p. 14.

[2] R. Tsu and L. Esaki, "Tunneling in a finite super-lattice," *Appl. Phys. Lett.*, vol. 22, p. 562, 1973.

[3] M. A. Frerking, "Quantum well multipliers: Triplers and quintuplers," *Proc. First Int. Symp. in Space Terahertz Technol.*, 1990, p. 320.

[4] P. H. Siegel, A. R. Kerr, and W. Hwang, "Topics in the optimization of millimeter-wave mixers," NASA Tech. Paper 2287, p. 398, 1984.

[5] E. Kollberg and A. Rydberg, "Quantum-barrier-varactor diodes for high-efficiency millimeter-wave multipliers," *Electron. Lett.*, vol. 25, p. 1696–1697, Dec. 12, 1989.