Progress Toward Solid-State Local Oscillators at 1 THz

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Abstract—**A varactor tripler to 800 GHz with 250 mW output power is reported. This tripler uses a new GaAs Schottky diode which has been optimized for high frequency applications. It features a smaller anode diameter and higher epitaxial doping density than previous varactor multipliers. The resulting output power is much greater than has been previously reported at such a high frequency.**

I. Introduction

THERE is a great need for compact and reliable sources of local oscillator power at frequencies throughout the submillimeter-wavelength range. The most direct method to achieve this goal is to use GaAs Schottky varactor diodes to multiply the output of GaAs- or InP-transferred electron oscillators (TEO's) to higher frequencies. The resulting all-solid-state sources are quite reliable, compact, relatively inexpensive, and have been space qualified. Unfortunately, previous attempts at achieving usable amounts of power in the 800-GHz range have resulted in output powers of about 100 μW and efficiencies of less than 1%. This is not suitable for most applications.

Our goal is to develop Schottky multiplier technology for use throughout the submillimeter wavelength range (300 GHz–3 THz) as local oscillator sources for SIS mixers and potentially Schottky mixers as well [1]. This letter presents recent results at 800 GHz in a tripler with whisker-contacted Schottky diodes. These diodes were designed by a new strategy that alleviates velocity saturation effects and was previously demonstrated at millimeter wavelengths [2]. The resulting output power of 250 μW is an important step toward our goal.

II. The Schottky Diode Design

The standard honeycomb style whisker contacted diode has been previously described and is well understood [3]. The primary design parameters are the anode diameter and the epitaxial layer doping density and thickness. The device characteristics that can be adjusted by varying these parameters are the junction capacitance, the series resistance, and the breakdown voltage. Previously, it was common to assume a required breakdown voltage to support the amount of available input power. This generally led to the use of rather low-doped and relatively thick epitaxial layers and, therefore, low cutoff frequencies. However, the recent realization that velocity saturation effects play a limiting role in varactor operation [4] has led us to re-evaluate our design process. The new design strategy is to reduce the epitaxial layer thickness to a value that is consistent with the saturated electron velocity. Our starting point is the equation

$$t_{\mathrm{epi}} = \frac{v_{\mathrm{sat}}}{2\pi\nu_p} \tag{1}$$

where ν_p is the pump frequency for the multiplier and v_{sat} is the assumed electron saturation velocity. The factor of two in the denominator is used because the electrons must travel the full length of the epitaxial layer in one-half of the pump cycle. Furthermore, since the electrons cannot possibly travel in the desired direction at the saturated velocity throughout the entire cycle (due to inertial and other high frequency effects), an additional factor should be added to the denominator. We have chosen a factor of π.

Recently, Louhi and Räisänen [5] have proposed an optimal epitaxial layer thickness of

$$t_{\mathrm{epi}} = \frac{v_{\mathrm{sat}}}{2\nu_o} \tag{2}$$

where ν_o is the output frequency. For the presently considered case of a tripler, this equation gives nearly the same result as our assumption. To determine the exact value of the optimum epilayer thickness is no easy task. At these frequencies, it would require accurate consideration of time-dependent electron motion including velocity overshoot in thin epitaxial layers with an accurate model of the boundary condition presented by the Schottky contact. Although others are working to develop such analyzes [5]–[7], they are beyond the scope of the present work, which is primarily experimental in nature.

Since higher doping density yields lower series resistance and gives the diode the ability to carry more current, we should choose the highest doping possible. However, the limitation is that the diode should not undergo avalanche breakdown before the full epitaxial thickness, t_{epi}, is depleted. Thus, we choose the doping for which breakdown occurs just as the depletion region width equals t_{epi}. To solve for the epitaxial doping density, N_{epi}, we use a standard empirical approximation of the breakdown voltage as a function of doping in GaAs [8] and the standard expression for depletion layer width at the breakdown voltage as given by the depletion approximation, given, respectively, as

$$V_{\mathrm{br}} = 60\left(\frac{E_g}{1.1}\right)^{3/2}\left(\frac{N_{\mathrm{epi}}}{10^{16}}\right)^{-3/4} \tag{3}$$

where V_{br} and the energy gap, E_g, are expressed in V and

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TABLE I
NOMINAL DIODE PARAMETERS

Diode Batch	Epitaxial Doping Density (cm^{-3})	Epitaxial Thickness (μm)	Anode Diameter (μm)	Series Resistance (Ω)	Breakdown Voltage (V)	Zero-bias Capacitance (fF)
2T2	1×10^{17}	0.59	2.5	12.5	11	5.5
2T14	2.3×10^{17}	0.24	2.1	8.5	7.2	3.9

$N_{\rm epi}$ is in units of $\rm cm^{-3}$, and

$$W = \sqrt{\frac{2\varepsilon}{qN_{\rm epi}}(V_{\rm bi} + V_{\rm br})}. \tag{4}$$

The final choice is the anode diameter. This parameter controls the trade-off between the zero-bias junction capacitance and the series resistance. At this point, we generally rely on the circuit designer to choose a capacitance range that should allow good coupling to the multiplier circuit. Simply scaling the capacitance from previous lower frequency triplers, we conclude that a zero-bias capacitance of 3–5 fF is an appropriate starting point at 800 GHz. Table I describes our previous best diode design for high-frequency multipliers (2T2) and the new design, designated 2T14.

If we assume a saturated electron velocity of 3×10^7 cm/s [5], [9] and the tripler pump frequency of 268 GHz, then (1) yields a epitaxial layer thickness of 0.18 μm. Thus, the older 2T2 design clearly has more epitaxial material than can be depleted of electrons and refilled within a pump cycle. Thus, it should not be expected to work well at this frequency. The newer diode, however, is much closer to the design thickness (particularly in light of the approximate nature of the design rules) and should therefore be less affected by velocity saturation effects. Furthermore, it has lower series resistance and lower junction capacitance, leading to greater efficiency. The trade-off is, of course, reduced breakdown voltage. However, since velocity saturation effects prevent the full thickness of the 2T2 epitaxial layer from being used, this is not a clear disadvantage.

III. MEASURED TRIPLER RESULTS

The tripler design used for these measurements has been previously described [1]. The output power was coupled to free space from the waveguide by an output feedhorn and measured with a Thomas Keating Power Meter [10]. The measured output power and efficiency as a function of the input frequency are listed in Table II. The peak output power at 804 GHz was measured to be 250 mW, a significant improvement over previous published results. At this frequency, the doubler in the ×6 multiplier chain supplied 7.5 mW, yielding a tripler efficiency of roughly 3.3%. It is important to note that at each frequency the efficiency was measured only at the greatest input power level.

TABLE II
MULTIPLIER PERFORMANCE

RPG Gunn-Osc		Doubler			Tripler			System
V_{out} (GHz)	P_{out} (mW)	V_{out} (GHz)	P_{out} (mW)	η (%)	V_{out} (GHz)	P_{out} (μW)	η (%)	η (%)
135	33	270	6.4	19	810	70	1.1	0 2
134	37	268	7.5	20	804	250	3.3	0.7
133	40	266	8	20	798	225	2.8	0 6
132	40	264	9	23	792	130	1.4	0.3
131	42	262	10	24	786	110	1.1	0.3
130		260			780	140		
129		258			774	130		
128		256			768	80		

IV. CONCLUSION

GaAs Schottky barrier varactor diodes used as frequency multipliers are presently the best source of reliable local oscillator power for many submillimeter-wavelength systems. However, these diodes are prone to velocity saturation, which not only seriously degrades performance, but makes the simulation of the diode in the multiplier circuit quite complex. To avoid these problems we have developed a new diode design strategy that helps to alleviate the velocity saturation effects. This work represents the first implementation of this strategy at submillimeter wavelengths. The resulting tripler to 800 GHz has yielded record output power and efficiency. Further improvements are expected when more millimeter-wavelength pump power becomes available and with further refinements of the tripler diode and circuitry.

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