Capability of THz sources based on Schottky diode frequency multiplier chains

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Abstract — We have developed and tested a number of fixed-tuned GaAs Schottky diode frequency doubler and tripler designs covering over 50% of the 100 – 2000 GHz band, with best measured 120 K peak efficiencies ranging from 39% for a 190 GHz doubler to 0.94% for a 1800 GHz tripler. We find that the efficiencies across this broad range of frequency and performance can be well-described by a simple empirical exponential decay model. This model can be used to predict achievable performance for Schottky diode frequency multipliers and multiplier chains, and gives an indication of what chain configurations are most likely to produce optimal results to reach a given frequency range. Extrapolating the models beyond the highest frequencies tested predicts that cooled Schottky diode frequency multiplier chains are capable of producing at least 1 µW at 2.5 THz.

Index Terms — Schottky diode frequency converters, submillimeter wave frequency conversion, submillimeter wave generation, frequency conversion, varactor.

I. INTRODUCTION

Prior to the development of THz Schottky diode frequency multiplier chains, heterodyne receivers above about 1 THz had to be pumped with local oscillators consisting of gas FIR lasers. Such oscillators are massive, bulky, difficult to operate, require large amounts of power, and only operate at specific discrete frequencies. Thus, the recent development of tunable solid state THz sources represents a major advancement for the THz field. The purpose of this paper is to present recently measured results that suggest a pattern which can be extrapolated to predict power levels for future single chain local oscillator sources.

The results presented here are for planar Schottky diode multipliers electronically tunable for 10-15% bandwidth. Power amplifiers driven by commercial synthesizers produce 100 to 150 mW at W band [1]. One to four frequency doublers and/or triplers are cascaded after the W band source. All multipliers are balanced designs implemented with monolithic circuits mounted in split waveguide blocks. The frequency doublers each have two parallel branches of diodes, while the triplers each have two branches of diodes in an anti-parallel configuration. The low frequency multipliers (below 1 THz) use "substrateless" technology implemented with 1 to $2 \cdot 10^{17}$ cm^{-3} doped GaAs, while the multipliers above 1 THz are fabricated on 3 µm thick GaAs membranes with $5 \cdot 10^{17}$ cm^{-3} doped anodes [2]-[5]. The first stage multipliers have 3 anodes in series in each branch (for 6 anodes total), and the second stages have 2 series anodes in each branch (for 4 anodes total). All multipliers above 700 GHz have only 1 anode per branch, or 2 anodes per multiplier. Multipliers with output frequencies above 1 THz have diagonal horns integrated into the waveguide split blocks. The multipliers are described in detail elsewhere [6]-[10].

II. MEASUREMENTS

The measurements were performed at room temperature and at 120 K. The W band power from the power amplifier was monitored with a directional coupler and power meter. An Erickson calorimeter [11] with waveguide input was calibrated with a DC load and used for all room temperature power measurements below 1.4 THz. A Keating meter was calibrated with a DC square wave and lock-in amplifier, and used for all other power measurements below 1.4 THz. Above 1.4 THz, measurements were made optically with a Golay cell calibrated against the Keating meter. All optical measurements were corrected for the losses in Mylar windows, where applicable, but were not corrected for other optics losses including non-ideal mirror reflectivity and air. Waveguide measurements were *not* corrected for loss in the connecting waveguides between the device under test and the meter.

For practical reasons related to the high frequencies involved, it is not possible to measure multiplier input power above 110 GHz directly. Instead, the driver chain for each measurement was measured separately, and assumed to not change significantly when the device to be

TABLE I
SUMMARY OF MEASURED EFFICIENCIES

Design	295 K			120 K		
	Freq (GHz)	5% B.W. (%)	Peak (%)	Freq (GHz)	5% B.W. (%)	Peak (%)
190 GHz doubler	190	30.6	33.5	185	32.8	39
200 GHz doubler	194	28.1	31.8	200	29.4	38.3
375 GHz doubler	370	14.7	18.5			
400 GHz doubler	385	14.9	18.3	370		28
750 GHz doubler	730	6.7	10.5			
800 GHz doubler	775	10.4	13.5			
1500 GHz doubler	1510	1.1	3.5	1510	2.6	5.2
600 GHz tripler	540	5.3	10	580	6.1	10
1200 GHz tripler	1200	1.3	1.9			
1800 GHz tripler	1740	a	a 0.2	1740	0.32	0.94

Notes: [a] Drive power was insufficient to reach maximum efficiency.

tested was added. Due to the nonlinear nature of the frequency multipliers, this assumption is not strictly true, and so input power measurements should be treated as estimates. Although in some cases peaks and valleys associated with structure in the driver chain may shift in frequency when the device to be tested is added to the chain, this effect is easy to spot and correct for. That accounted for, the uncertainty of the input power estimates is unlikely to be higher than about 20%. A summary of all measured efficiencies is given in Table I.

III. EMPIRICAL MODELS

Based on computer simulations using reasonable assumptions for diode parameters, Erickson predicted that solid state multipliers should work well above 1 THz [12]. Since then, by improving modeling, planar device technology, and waveguide fabrication we have now demonstrated appreciable power up to 1800 GHz.

The measured efficiencies of our planar multipliers are given in Table I. These data can be fit with an equation of the form

$$\eta(f) = \eta_0 \cdot e^{f/f_0}. \qquad (1)$$

The constants η_0 and f_0 are different for doublers and triplers, as well as for different temperatures or required bandwidths. A summary of η_0 and f_0 determined from the measured data in Table I is given in Table II. Note that all designs were optimized for 10-15% bandwidth: peak performance could be improved by reoptimizing the design for a narrower frequency range.

It is convenient to calculate the efficiency of N cascaded doublers or triplers. In this case,

$$\eta(f) = \eta_0^N \cdot Exp\left[\frac{f}{f_0} \cdot \sum_{i=0}^{N-1} 2^{-i}\right]. \qquad (2)$$

Thus, the efficiency of cascaded multipliers exhibits the same exponentially decaying behavior as a single multiplier, except with effectively reduced η_0 and f_0.

Fig. 1 shows predicted output power for a variety of chain configurations. The input power is assumed to decrease linearly from 200 mW at 70 GHz to 60 mW at 150 GHz, and efficiencies are based on the predictions in Table II for 120 K operating temperature and 5% bandwidth. For comparison, sample 120 K measurements are included directly in the figure. The chain input power for the measurements was 150 mW in the 88-106 GHz band. It can be seen in the figure that for the assumed input power profile, different configurations of doublers and triplers are predicted to have very similar performance.

To achieve the predicted performance, multiplier designs must be well optimized. Input power must be sufficient to operate near the point of maximum efficiency. However, maximum efficiency is usually met

TABLE II
EFFICIENCY MODEL PARAMETERS

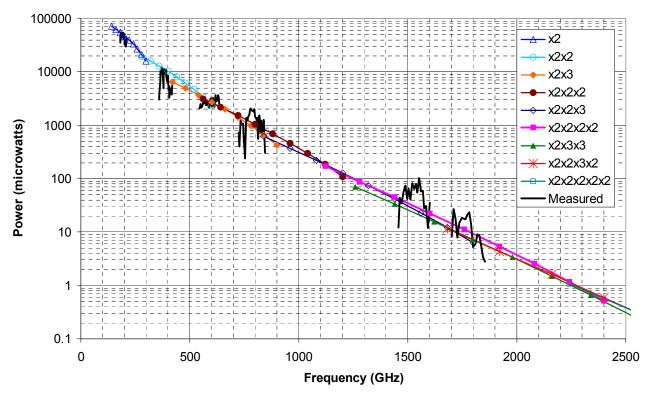| Description	η_0	f_0 (GHz)
Doubler, 295 K, Peak	0.45	600
Doubler, 295 K, 5% B.W.	0.45	410
Doubler, 120 K, Peak	0.50	650
Doubler, 120 K, 5% B.W.	0.47	520
Tripler, 120 K, Peak	0.32	490
Tripler, 120 K, 5% B.W.	0.27	390

Fig. 1. Predicted and measured output power for a variety of chain configurations at an operating temperature of 120 K. Predictions are based on 5% bandwidth fit parameters from Table II. The assumed chain input power decreases linearly from 200 mW at 70 GHz to 60 mW at 150 GHz. The chain input power for the measurements was 150 mW in the 92-106 GHz band. Note that different configurations with the same output frequency may have different input frequencies.

at about the same drive level as the maximum safe input power. Operating at input power levels above the maximum efficiency point may reduce the lifetime of the anodes. Fabrication and assembly tolerances must be tight, with errors less than about $\lambda/30$. Anodes must have good DC IV characteristics. For the data presented here, the fraction of fabricated multipliers that operate near the best measured performance drops from about 1/2 at 200 GHz to less than 1/5 at 1800 GHz. For the best possible chain, the frequency response of all multipliers in the chain must be well matched.

The fit results in Table II predict that a chain of 5 cascaded doublers to 2.5 THz could have peak efficiency as high as 0.0018% and 5% bandwidth with efficiency better than 0.0002%. While fabrication of the waveguide circuit and device will be challenging, it should be possible to produce more than 1 µW at 2.5 THz.

IV. CONCLUSION

We have shown that for a given operating temperature and required bandwidth, the efficiency of frequency multipliers over more than a decade in frequency can be well described by a simple 2 parameter exponentially decaying model. The available drive power and power handling of the driver stages of a multiplier chain have major impact on the achievable output power, and best performance can only be achieved if all designs and power levels are well optimized everywhere in the chain. A sustained effort should be able to produce over 1 µW at 2500 GHz from a cooled multiplier chain.

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