A High-Power W-Band Quasi-Optical Frequency Tripler

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Abstract—**A monolithic W-Band quasi-optical array consisting of 196 heterostructure barrier varactors mounted in a waveguide has produced 684 mW of CW output power with a peak conversion efficiency of 11.3% at 93 GHz. The compact 32 mm^2 array was fabricated using two-barrier twin-mesa varactors with InGaAs/InAlAs/AlAs barriers on a lattice-matched InP substrate. Device measurements demonstrate low series resistance and high cutoff frequency. Simulations show even greater output power and efficiency can be achieved by increasing the device density in the array.**

I. INTRODUCTION

A compact and low-cost solid-state high power source at W-band is becoming increasingly necessary to meet the performance requirements of modern communication and instrumentation systems. Traditionally, traveling-wave-tube (TWT) power amplifiers have been used, but such amplifiers tend to be too bulky, heavy, and expensive for use in the next generation of systems intended for high-bandwidth communications. Solid-state transistor power amplifiers based upon GaAs or InP HEMT devices with 0.1μm gate length are a promising lightweight alternative to the TWT. However, the highest power monolithic HEMT MMIC power amplifier reported to date exhibits a saturated power of 427 mW at 95 GHz [1], which is still too low for many applications. Combining multiple MMIC power amplifiers to obtain higher power has been demonstrated, but is complicated and expensive [2]. In contrast, monolithic quasi-optical frequency tripler arrays based on heterostructure barrier varactor (HBV) devices have exhibited output powers as high as 5 W (pulsed) at 99 GHz in a Gaussian focused-beam beam system [3]. Furthermore, frequency triplers promise to be low cost because the varactor devices do not require the submicron fabrication complexity of a 0.1μm HEMT transistor, and can be driven with inexpensive and efficient lower frequency sources. This work expands upon these earlier results by demonstrating a high-power quasi-optical tripler in a compact waveguide package with nearly an order of magnitude improvement in efficiency than previously demonstrated.

The heterostructure barrier varactor (HBV) is frequently used to generate power at millimeter-wave frequencies (Fig. 1). The symmetric capacitance-voltage relationship of the HBV can simplify circuit design because it eliminates the need for idler circuit termination of the even harmonics, and a dc bias network is not required [4]. For good multiplying efficiency, the varactor used in a multiplier should have a high dynamic cutoff frequency. This is typically achieved by reducing the diode area so as to reduce the minimum capacitance (C_{min}) and still maintain low series resistance. However, the small diode area coupled with low single-barrier breakdown voltage limits power handling. Stacking the barriers epitaxially is often used to increase the breakdown voltage and cutoff frequency of the varactor still further. A record 19.6dBm output power with 9.1% conversion efficiency at 93 GHz has been demonstrated with a ten-barrier HBV device [5]. However, fabrication constraints and increasing series resistance ultimately limit the number of barriers that can be stacked in series, placing an upper bound on the total power that this approach can generate. To overcome this limitation, quasi-optical power combining can be used to combine the outputs of hundreds of devices in free space with high efficiency and low cost. Thus, the quasi-optical tripler can produce output powers 20 to 30 dB greater than that of a single device allowing for the efficient generation of high power at W-band.

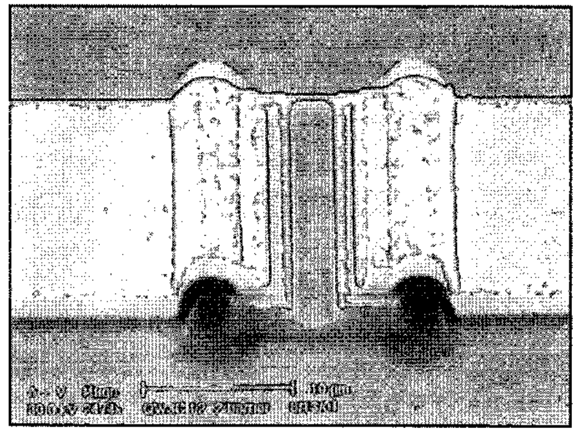

Fig. 1. SEM photograph of a 4x20 μm^2 HBV device. The two mesas are electrically connected at the base by the buried n+ InGaAs layer. Air-bridged metal is used to connect to the top of each of the two mesa stacks. The n+ layer is etched away around the perimeter of both stacks to isolate devices from each other.

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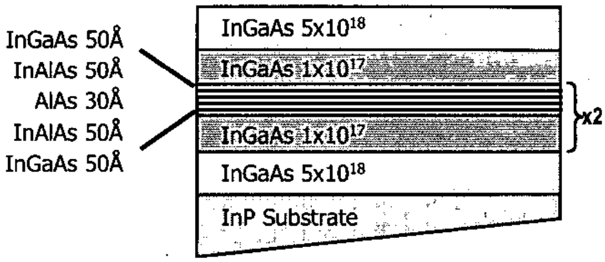

Fig. 2. Epitaxial structure for the heterostructure barrier varactor used in the array (two barrier sequence shown). One and three barrier wafers were also fabricated.

II. DEVICE DESCRIPTION AND CHARACTERIZATION

Fig. 2 shows the epitaxial layer structure grown on a semi-insulating three-inch diameter InP substrate used in the fabrication of the HBV devices. This layer system has been demonstrated to have a number of advantages over an equivalent GaAs based device [6]. In particular, the InGaAs/InAlAs/AlAs barrier increases the barrier height by more than a factor of three compared to GaAs/AlGaAs devices resulting in higher breakdown voltage, while the compact layer structure reduces series resistance. A two-barrier system was chosen as it provided the best balance amongst breakdown voltage, series resistance, and fabrication complexity for this application compared to the one and three barrier wafers that were also investigated.

Fig. 1 shows an SEM image of a 4x20μm^2 double mesa device. The two mesa stacks are electrically isolated from each other by a trench etched down to the buried heavily

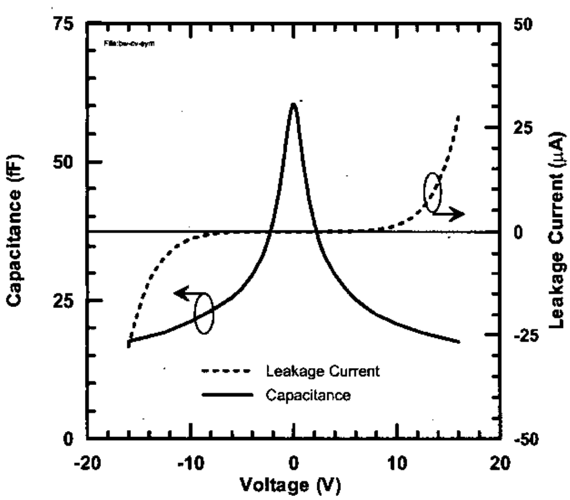

Fig. 3. Measured small signal capacitance (averaged from 1 to 50 GHz) and leakage current characteristics versus applied voltage for the 80μm^2 two-barrier twin mesa device shown in Fig. 1.

TABLE I

SUMMARY OF TWO BARRIER TWIN MESA DIODE CHARACTERISTICS

Parameter	Measured Value
Maximum capacitance	C_{max} ~ 3.0 fF/μm^2 per barrier
Breakdown voltage	V_{bk} ~ 5V per barrier
Leakage current density	J ~ 1.5 μA/μm^2 at V_{bk}
Capacitance ratio	C_r ~ 3.3
Series resistance	R_s ~ 4.8 Ω (80μm^2 device)
Cutoff frequency	f_c ~1100 GHz

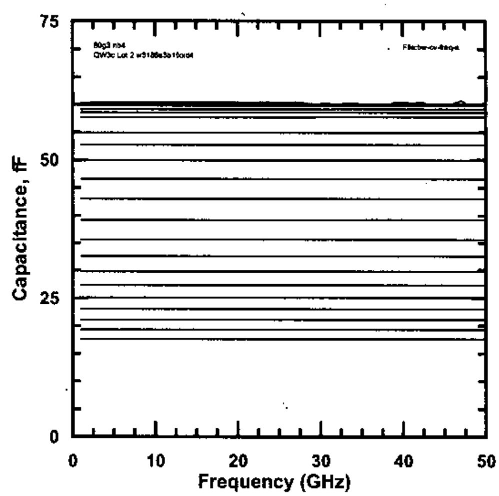

Fig. 4. Measured small signal capacitance versus frequency for applied voltages from 0 to 16 V for the 80μm^2 two-barrier twin mesa device shown in Fig. 1.

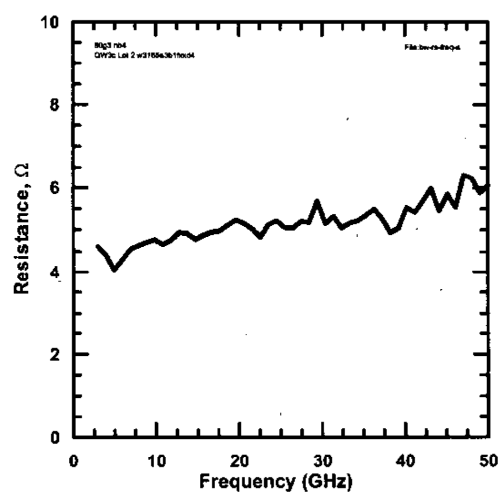

Fig. 5. Measured small signal series resistance versus frequency for an applied voltages of 0 V for the 80μm^2 two-barrier twin mesa device shown in Fig. 1.

doped InGaAs layer, which serves to electrically connect the stacks at the base. This back-to-back stack results in a doubling in the number of barriers for a given epitaxial layer profile. Additionally, it ensures that device characteristics remain symmetrical, even with slight variations in the epitaxial profile layer thicknesses.

To characterize the device, CPW test structures with the device mounted in shunt and series were measured to 50 GHz using a network analyzer and on-wafer probes. The CPW pad parasitics were deembedded by fitting the pad s-parameters from a full electromagnetic analysis of the CPW pad circuit using a 2.5D field solver to an equivalent circuit model, and then inverting the model. Fig. 3 shows plots of the measured capacitance (C-V) and current (I-V) curves versus applied voltage for an 80μm^2 double barrier wafer. The highly symmetric capacitance curve ensures good rejection of even mode harmonics during multiplication. Table 1 summarizes the key measured parameters of the device. Fig. 4 shows the measured capacitance versus frequency after deembedding pad parasitics for a range of applied voltages. The flat response to 50 GHz is a good indication of the high cutoff frequency of the device and the accuracy of the deembedding process. Similarly, Fig. 5 shows the measured series resistance versus frequency. The slight increase in resistance with frequency is presumably due to the skin effect. The low measured series resistance compares favorably with the state of the art [6].

III. Quasi-Optical Array Circuit Design

Fig. 6 shows a cutaway depiction of the quasi-optical tripler array and filter/matching surfaces in its waveguide fixture. The array is thinned and mounted to a diamond

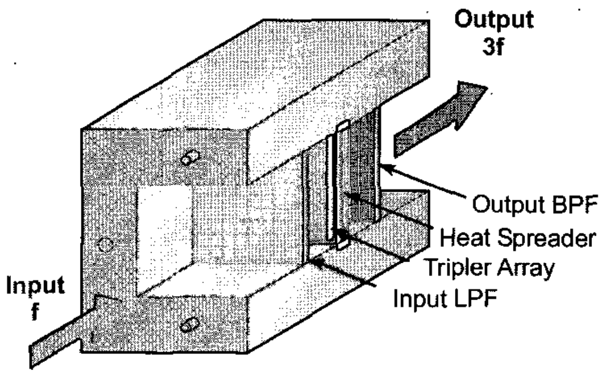

Fig. 6. Cutaway view of the quasi-optical tripler array and filter/matching slabs in a waveguide fixture. The 6x6 mm square guide is tapered to mate with a wr-28 guide on the input and a wr-10 guide on the output. The InP tripler array is bonded to a thermal spreader. Input and output FSS filters are designed to terminate unwanted harmonics with an optimized shunt susceptance

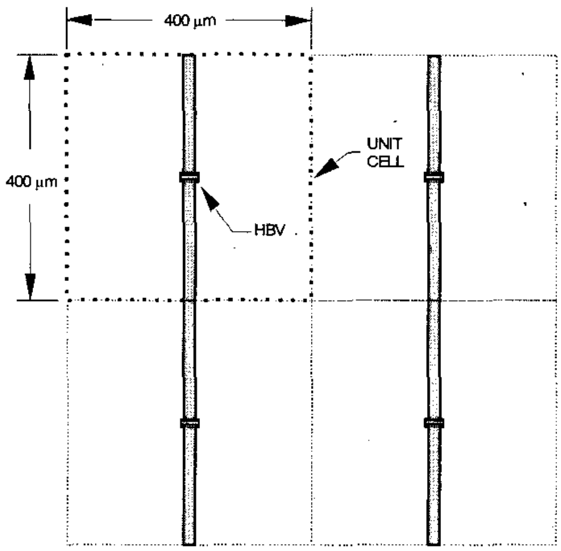

Fig. 7. Array unit cell structure showing a prototypical 2x2 element array. The dipoles from each unit cell connect at the unit cell boundaries to form one long trace for each column of the array.

heatsink for thermal management. The input low-pass filter consists of a two-layer square capacitive mesh frequency selective surface formed of evaporated gold on a thinned semi-insulating GaAs substrate. Similarly, the output bandpass filter consists of a two-layer inductive strip frequency selective surface also on a GaAs substrate. Additional quartz and GaAs matching slabs surround the filters and active array to properly match the circuit to the input and output wave impedances.

The monolithic InP 14x14 element array consists of 4x20 μm^2 HBV devices connected in series with vertical evaporated-gold dipole antennas as shown in Fig. 7. The 400-μm square unit cell size results in an array size of 5.6mm on a side.

IV. Large Signal Simulations and Measurements

The HBV device is modeled using an equation-based custom nonlinear model using Agilent ADS symbolically defined device (SDD) components. The model parameters are fit to measured rf and dc data using Agilent ICCAP and can be scaled afterwards for different diode area and number of barriers. The filters and passive parts of the array are simulated using Ansoft HFSS, a full-wave electromagnetic solver, to correctly account for the field variation across the TE_{10} metal walled waveguide test fixture. The entire system, including filters, array, devices, and matching slabs is then combined and simulated in Agilent ADS using the harmonic balance technique. The matching slab thicknesses

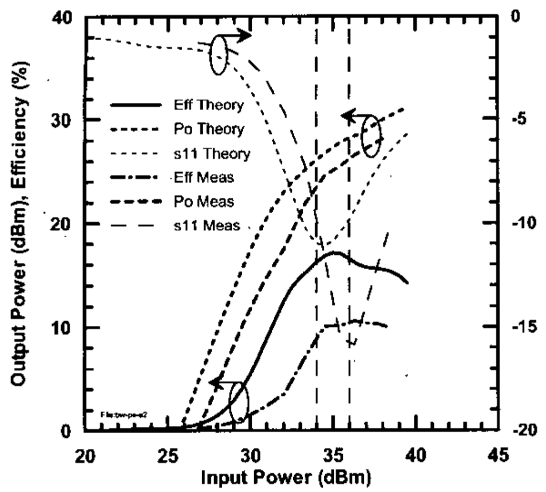

Fig. 8. Theoretical output power, efficiency and return loss versus input power at 93 GHz for the 14x14 element array in a metal walled waveguide test fixture. Superimposed on the plot are the measured output power, efficiency and return loss showing good agreement with theory. The peak measured output power is 694 mW and the peak measured efficiency is 11.3%.

were then optimized for best tripling efficiency. Once the slab thicknesses were found, the slabs were lapped and cut for insertion into the fixture.

Fig. 8 shows a plot of measured output power and efficiency at 93 GHz versus input power. Superimposed on the plot are the simulated output power and efficiency. Good agreement is observed between measurement and theory, with the difference attributed to unmodeled effects. In particular, the losses in the input and output waveguide transitions were not included in the simulation and are estimated to have approximately 1 dB of total loss. Furthermore, the effect of imperfect diode yield, which was measured to be approximately 95% across the array, was also neglected. The peak measured CW output power at 93 GHz is 684 mW (28.4 dBm) and the peak measured conversion efficiency is 11.3%. The measured conversion efficiency is more than five times higher than the best previously reported (pulsed) quasi-optical tripler array result [3]. It is even better than the best-reported single HBV device performance of 19.6 dBm and 9.1% conversion efficiency at 93 GHz [5] while having 7.5 times more output power.

Primarily the breakdown voltage of the HBV varactors, rather than thermal constraints, limits the output power of the array reported here. Simulations show that substantially more output power can be obtained by increasing the density of the devices in the array, thereby reducing the peak rf voltage on each device for a given excitation power. Placing the array in a waveguide with a uniform TEM-like field distribution can further improve efficiency and power, compared to the TE_{10} excitation used here, because all devices in the array will then be uniformly excited. Such a guide may be constructed using electromagnetic crystal sidewalls as reported by Kim [7]. Assuming such a guide, with a 900-element array of three-barrier twin-mesa devices, simulations show a tripler array with an estimated output power of 20 W and a conversion efficiency of 25% is feasible.

V. Conclusions

A high-power, high-efficiency quasi-optical w-band tripler consisting of an array of 196 HBV InP varactors mounted in a compact metal-walled waveguide has been fabricated. A CW output power of 684 mW and a peak conversion efficiency of 11.3% were measured. The measured results agree closely with theory. The tripler array is suitable for applications requiring a low-cost, compact, solid-state power source at W-band; applications include modern low-cost communication and instrumentation systems.

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