Planar Multibarrier 80/240-GHz Heterostructure Barrier Varactor Triplers

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***Abstract*— Prototype planar four barrier GaAs/$Al_{0.7}Ga_{0.3}$As heterostructure barrier varactors (HBV's) for frequency tripling from 80 to 240 GHz have been fabricated using a process in which the device *surface channnel* is etched prior to the formation of the contact pad-to-anode air-bridge *finger*. Formation of the device air-bridge finger after etching the surface channel is facilitated by a trench planarization technique and yields a device with minimal parasitic capacitances. Planar four-barrier HBV triplers with nominal 10-μm diameter anodes have been tested in a crossed-waveguide tripler block; as much as 2 mW of power has been generated at 252 GHz with a flange-to-flange tripling efficiency of 2.5%. These devices are the first planar or multibarrier HBV triplers reported and their output powers are nearly double that of previous whisker-contacted single-barrier HBV's.**

***Index Terms*— Frequency conversion, millimeter-wave diodes, semiconductor heterojunctions, varactors.**

I. Introduction

The heterostructure barrier varactor (HBV),[1] first proposed in 1989 [1], has received considerable attention as a promising device for high efficiency frequency multiplication in the millimeter to submillimeter wavelength range because of its attractive device characteristics and flexible design parameters. A single-barrier HBV consists of a large bandgap semiconductor sandwiched between symmetric moderately doped modulation regions of smaller bandgap material such that the device has an evenly symmetric nonlinear capacitance–voltage (*C–V*) relationship of about zero dc bias. This evenly symmetric device *C–V* characteristic eliminates the even harmonic components from the output current waveform so that high efficiency frequency multiplier circuits, which do not require dc bias and which require fewer idlers than the standard Schottky-barrier varactor (SBV) multipliers, can be realized. These device characteristics make the HBV an ideal device for use in high-order frequency multipliers, broadband frequency multipliers, and quasi-optical tripler arrays. The HBV is ideally suited for use as the multiplier element in a quasi-optical tripler array since no idlers are required for frequency tripling and dc bias is not required for the individual elements in the array.

By epitaxially stacking several single-barrier HBV's in series, further advantages are obtained including increased device impedances for a given device area, higher device cutoff frequencies for a given device area due to reduced device capacitances, higher power handling capabilities due to the distribution of pump power over several series devices, and increased heat dissipation capabilities for a given capacitance modulation range due to increased device areas. Overall, the HBV has a large degree of design flexibility in that the semiconductor alloy composition and doping profiles, barrier thickness, number of barriers, device geometry, and device area can all be varied. Ultimately, the design flexibility and attractive device characteristics of the HBV suggest that a high efficiency frequency multiplier with excellent device/circuit impedance matching and near-optimum *C–V* relationship can be achieved with a single device.

In this paper, the fabrication and testing of the first planar or multiple-barrier HBV is described; a total of four GaAs/$Al_{0.7}Ga_{0.3}$As heterostructure barriers have been used in the devices. The devices were designed using the previously described numerical device/harmonic-balance circuit simulation technique [2]–[5] assuming optimum embedding impedances at the fundamental, as well as the second, and third harmonics. The device fabrication process is similar to that used to fabricate the planar University of Virginia (UVA) surface channel Schottky diode [6], [7]. Overall, the planar HBV described in this paper was designed to have roughly the same terminal characteristics and dynamic cutoff frequency as the UVA 6P4 GaAs SBV [8].

II. Device Fabrication

Unlike the SBV where the cross-sectional area controlling charge modulation is defined by the area of the anode, charge modulation in an HBV is controlled by the cross-sectional areas of both the barrier and modulation regions of the device. As a result, the fabrication of planar HBV's requires either an ion implant isolation step or a mesa-

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[1] Although this device was originally called the quantum barrier varactor (QBV) and is often called the single barrier varactor, it is called the HBV throughout this paper to avoid confusion with the Schottky barrier varactor (SBV) and to emphasize the importance of the heterostructure alloy composition and doping profiles in the design and operation of the device.

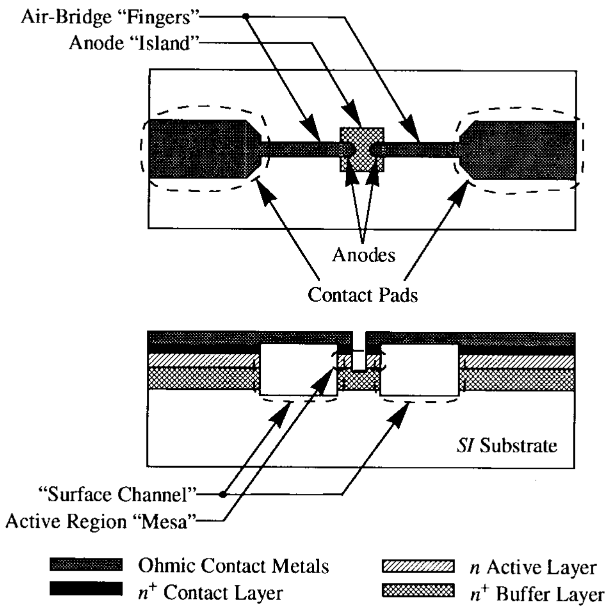


Fig. 1. (Top) Top view of the planar HBV device layout. (Bottom) Cross-sectional view of the planar HBV device layout.

TABLE I
UVA-NRL-1174 TWO BARRIER GaAs/AlGaAs HBV MATERIAL STRUCTURE

	Layer Thickness	Layer Doping	Material
n^+ Contact Layer	100 Å	n^+	InAs
	400 Å	n^+	$In_{1.0\text{-}0.0}Ga_{0.0\text{-}1.0}As$
	3000 Å	n^+	GaAs
n Active Layer	2500 Å	n ($8x10^{16}$ cm^{-3})	GaAs
	35 Å	i	GaAs
	200 Å	i	$Al_{0.7}Ga_{0.3}As$
	35 Å	i	GaAs
	5000 Å	n ($8x10^{16}$ cm^{-3})	GaAs
	35 Å	i	GaAs
	200 Å	i	$Al_{0.7}Ga_{0.3}As$
	35 Å	i	GaAs
	2500 Å	n ($8x10^{16}$ cm^{-3})	GaAs
n^+ Buffer Layer	4 μm	n^+	GaAs
Substrate	450 μm	SI	GaAs

isolation etch step to define the active region of the device. In this paper, planar mesa-isolated HBV's have been produced using a fabrication procedure in which the device *surface channel* is etched prior to formation of the contact pad-to-anode air-bridge *finger* [9]. Formation of the device air-bridge finger after etching the surface channel is facilitated by using the trench planarization technique of [9]; the basic concept underlying this planarization technique was first proposed in [10]. This process simplifies the surface channel etch, avoids galvanically enhanced etching at the finger/anode edge, and yields a device with minimal parasitic capacitances since the fringing capacitances between the device active region *mesa* and the air-bridge finger are minimized.

Although the present focus is on HBV's, the surface channel etch/epoxy planarization/finger electroplating process is applicable to a wide variety of planar devices. As suggested in [9], for example, the performance of the UVA surface channel Schottky diode [6], [7] could be improved if its fabrication procedure were modified to accommodate the surface channel etch/epoxy planarization/finger electroplating process.

The basic planar HBV device layout used in this work is shown in Fig. 1. This back-to-back layout yields an inherently multibarrier device; it has been utilized here to compensate for any asymmetry in the epitaxial device structure and to double the number of barriers obtained from a given HBV epitaxial structure. An overview of the general planar HBV fabrication process developed for this work is given below:

1) deposit ohmic contact metallization in device anode and contact pad regions using a dual-layer photoresist/electron-beam evaporation lift-off process, and alloy ohmic contacts in a forming gas ambient (90% N_2/10% H_2);
2) form device surface channel to isolate anode and contact pad regions using a photoresist protection/reactive-ion etch process;
3) planarize device surface channel using a low-viscosity thermosetting epoxy and a planarizing superstrate;
4) after exposing the device contact pads and anodes by an O_2 plasma etch of the epoxy, spin a very thin layer of photoresist on the wafer to improve the uniformity of the bulk epoxy planarization step and redefine the device contact pads and anodes in the photoresist;
5) sputter deposit a Cr/Au *seed* metallization layer on the entire wafer, pattern contact pad-to-anode air-bridge finger structures in photoresist, and dc electroplate Au to form the entire contact pad/air-bridge finger/anode structures;
6) remove epoxy/photoresist planarization material using an O_2 plasma etch process;
7) isolate device anodes using a photoresist protection/reactive-ion etch process.

The fabrication process is completed by making dice cuts at the boundaries of the individual devices and lapping the backside of the wafer in order to thin the wafer and separate the individual devices, all while protecting the frontside of the wafer with a polymer protective coating.

Prototype planar four-barrier HBV's for tripling from 80 to 240 GHz were produced using the fabrication process outlined above. The GaAs/AlGaAs epitaxial structure for the prototype HBV's is given in Table I. The structures were grown by the Naval Research Laboratory (NRL) in a Vacuum Generators V80H molecular beam epitaxy (MBE) system on (100)-oriented semi-insulating (SI) GaAs substrates which had resistivities of 5.0–7.0 $\times 10^7$ $\Omega \cdot$ cm at 300 K. Alloy composition and silicon doping profiles as well as layer thicknesses for the NRL-grown structures were estimated based on values extracted from calibration structures grown in the MBE system.

Since the back-to-back planar HBV geometry requires a pair of small ohmic contacts, it is important to note that

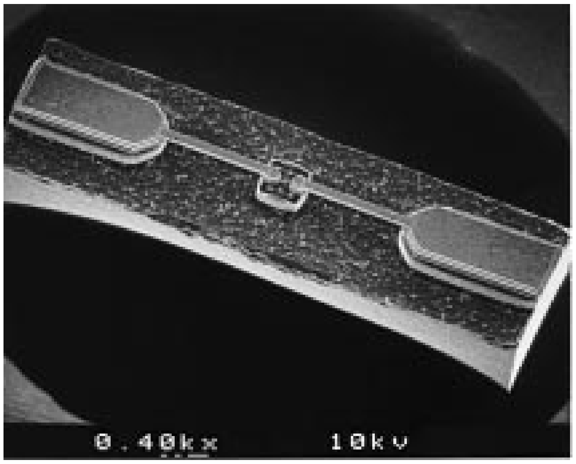


Fig. 2. Scanning electron micrograph of a planar four-barrier GaAs/$Al_{0.7}Ga_{0.3}As$ HBV chip (UVA-NRL-1174-K). The anodes are 8 μm in diameter, and the fingers are 4-μm wide.

the epitaxial structure shown in Table I includes an n^+ InAs/$In_{1.0-0.0}Ga_{0.0-1.0}As$/GaAs epitaxial capping layer to improve the specific contact resistivity of the resulting ohmic contacts [11], [12]. The metallization consisted of Ni(250 Å)/Ge(325 Å)/Au(650 Å)/Ti(400 Å)/Au(2000 Å) which was alloyed for two minutes at 375 °C. (TLM) test structures consisting of 100-μm wide by 150-μm long contact pads were fabricated on the HBV epitaxial material to determine the resistance of the ohmic contacts; average specific contact resistivities were approximately 7.0 $\times$ 10^{-7} $\Omega \cdot cm^2$.

For all devices, the contact pads were 30-μm wide and 60-μm long, while the fingers were 50-μm long and the anodes were spaced 5-μm apart. Fig. 2 shows a scanning electron micrograph of a completed prototype four-barrier GaAs/$Al_{0.7}Ga_{0.3}As$ HBV having 8-μm diameter anodes, 4-μm wide fingers, and a total chip thickness of approximately 2.25 . The etch depth for the device surface channel is approximately 10 μm, while the height of the anode mesas is approximately 3 μm. The actual anode diameter is slightly smaller than the target value since a 1.5 min 10:1 50% citric acid:H_2O_2 wet chemical etch was used to improve the quality of the mesa sidewalls and the anode isolation region following the device anode reactive-ion isolation etch.

III. Tripler Testing

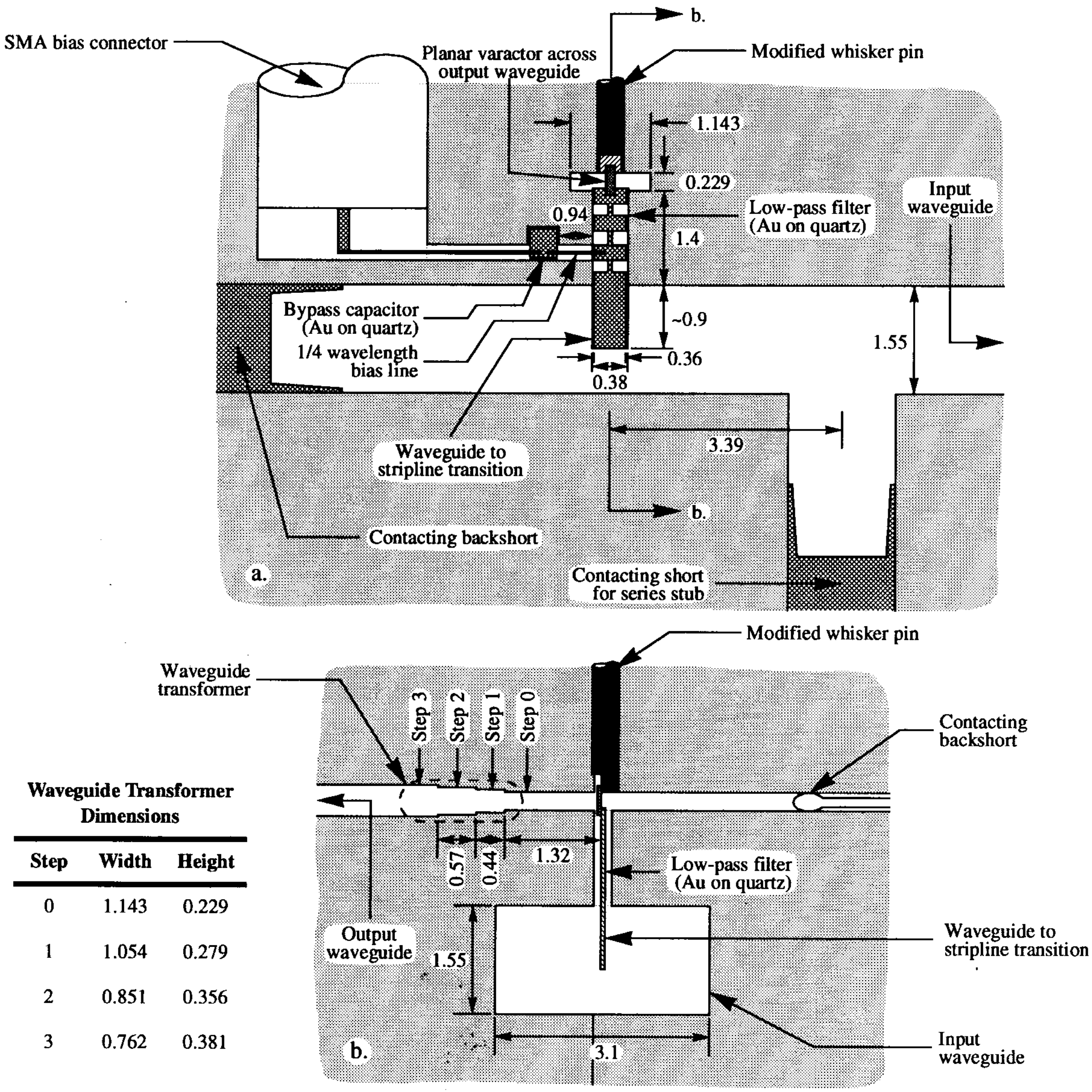
The tripler block used in this paper was a National Radio Astronomy Observatory (NRAO) block (A2621-TR2-T12) designed for use in the 200–290 GHz output frequency range [13]. The block employs a split-block construction with the input and output waveguides perpendicular to one another, and was originally designed for use with UVA 5M2 whisker-contacted GaAs SBV's having 5-μm diameter anodes and active region doping levels of 3.5 $\times$ 10^{16} cm^{-3}. Using UVA 5M2 and UVA 6P4 whisker-contacted GaAs SBV diodes, this tripler block provides more than 2 mW of power across the entire 200–290 GHz output band [13].

Fig. 3 is a detailed schematic diagram of the internal configuration of the tripler block utilized here. Input power is coupled to the device under test via a waveguide probe (waveguide to stripline transition) which extends into the WR-12 input waveguide. A stripline filter is integrated onto the waveguide probe to prevent power at harmonics above the fundamental from reaching the input waveguide. Near the device under testing, a two-section quarter-wave impedance transformer is used to couple the reduced-height backshort waveguide to the WR-3 output waveguide. The transformer, spaced approximately a half wavelength from the plane of the device under testing, acts as a reactive idler at the second harmonic frequency. The output waveguide is cutoff at both the fundamental and second harmonic frequencies. The block is equipped with three separate adjustable contacting short-circuit tuners; a backshort tuner and an E-plane tuner on the input waveguide, as well as a backshort tuner on the output waveguide. It is important to note that the output waveguide backshort is utilized to tune both the output circuit at the third-harmonic frequency and the idler circuit at the second harmonic frequency. Finally, dc bias to the device under test is provided via a 140-Ω transmission-line bias filter. The transmission line consists of a 1-mil diameter Au wire which is bonded between one of the low-impedance sections of the stripline filter and a 100-fF Au on quartz dielectric capacitor. The capacitor is enclosed in a rectangular shield machined into the block, and acts as an RF short-circuit which is transformed to an open-circuit at the stripline filter.

In order to support planar devices across the output waveguide (see Fig. 3(a)), the whisker pin of the block was modified as outlined in [14]. This minor modification involved milling out a flat surface on the side of the whisker pin such that the milled-out surface was in the plane of the top side of the stripline filter circuit. Ideally, the distance between the plane of this flat surface and the upper half of the block is approximately 3.5 (see Fig. 3(b)). As such, the planar HBV's were lapped to a thickness of about 2.25 to accommodate the combined heights of the epoxy used to secure the stripline circuit, the device, and the solder used to secure the device. The planar HBV's were mounted across the output waveguide by pressing the devices into indium bumps formed on the end of the stripline filter circuit and on the flat surface of the whisker pin.

The performance of the planar HBV triplers was evaluated using two types of measurements, which are: 1) output power versus frequency with 50 mW of input power; and 2) output power versus input power at the frequency of highest tripling efficiency. Losses in the tripler block have not been accounted for in the results presented in this paper. Except for output power versus input power measurements above 60 mW of input power, the test setup of Fig. 4 was utilized for all measurements. Due to excessive losses in the circulator, waveguide switch, and sections of waveguide between the input power source and the tripler block, the source was connected directly to the tripler block for measurements above 60 mW of input power.

The input power source for the measurement test setup of Fig. 4 is a mechanically tuned, low noise transferred electron oscillator (TEO) which produces up to 100 mW of power at frequencies from 68 to 87 GHz. The input power is measured using a Hewlett-Packard (HP) W8486A power sensor while the output power from the tripler block is measured using a PM103 Terahertz Absolute Power Meter System manufactured



Waveguide Transformer Dimensions

Step	Width	Height
0	1.143	0.229
1	1.054	0.279
2	0.851	0.356
3	0.762	0.381

Fig. 3. Schematic diagrams of the NRAO A2621-TR2-T12 200-290-GHz tripler block showing (a) the block split along the partition between the block halves and (b) a cross section through the block detailing the output waveguide transformer and device under test mounting configuration. Note that all dimensions are in millimeters.

by Thomas Keating, Ltd. The output power meter operates from 30 GHz to 3 THz, and employs a metal film coupled to a closed air-filled cell detector to measure the power contained in incident free-space beams via a modulated power to temperature to pressure conversion. Ultimately, the output voltage from a pressure transducer as measured by a lock-in amplifier represents the sensitivity of the power meter to the incident power. External thermal, optical, or acoustic sources of power were minimized by: 1) minimizing the distances between the tripler output horn antenna, the chopper blade, and the detector and 2) placing a sheet of absorptive material directly behind the chopper blade with only the tripler *horn* antenna passing through the sheet.

IV. Results

The prototype planar four-barrier $GaAs/Al_{0.7}Ga_{0.3}As$ HBV devices were analyzed to determine their dc current-voltage (*I–V*) and static *C–V* characteristics. The dc *I–V* characteristics were measured using an HP 4145B semiconductor parameter analyzer. The static *C–V* characteristics were measured using an HP 4275A multifrequency LCR meter with a local oscillator voltage between 0.01 and 0.04 V, and an excitation frequency of 4 MHz; the devices were biased using a Keithley 238 high-current source-measure unit. Fig. 5 shows the experimental dc *I–V* and static *C–V* characteristics of the UVA-NRL-1174-K planar four barrier $GaAs/Al_{0.7}Ga_{0.3}As$ HBV's with nominal 10-μm diameter anodes; a series impedance of 4.9 Ω has been estimated for these devices.

Using the test setup described in the previous section, the performance of the prototype planar four barrier $GaAs/Al_{0.7}Ga_{0.3}As$ HBV triplers was evaluated near the 80/240 GHz center frequency of the NRAO tripler block. Devices with nominal anode diameters of 10 μm (approximately 8.75 μm after wet etching) were tested. For an

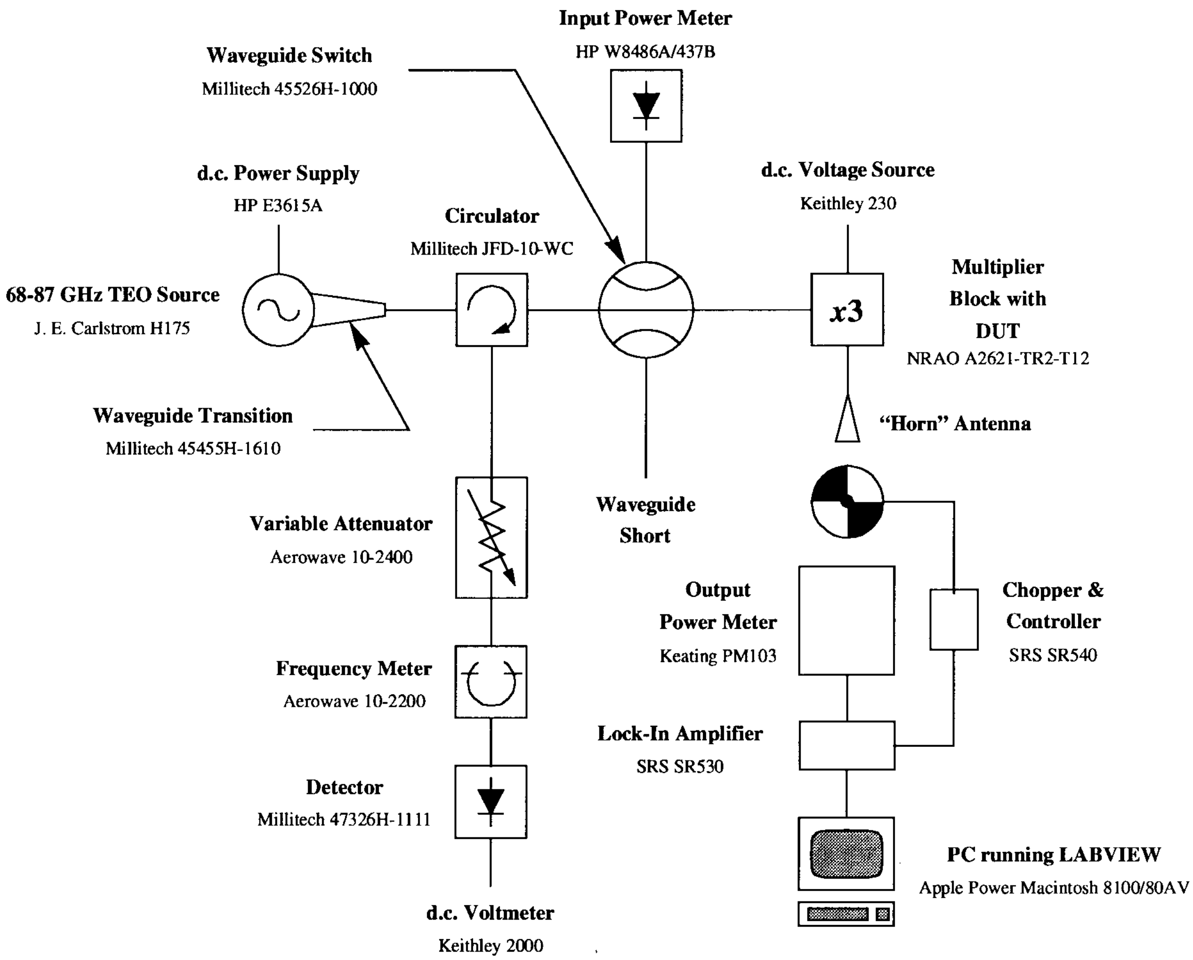


Fig. 4. Test setup for measuring the performance of frequency multipliers.

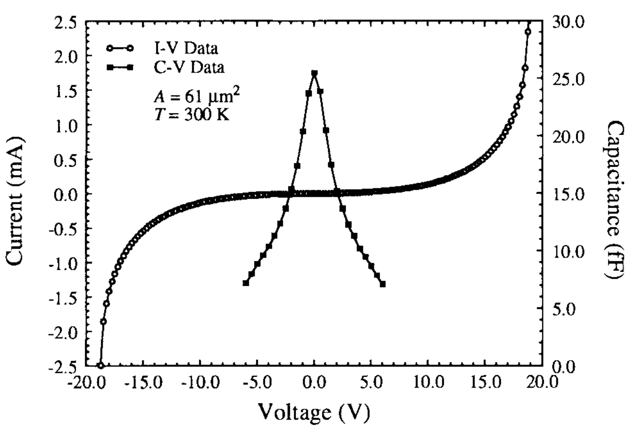


Fig. 5. Experimental dc *I–V* and static *C–V* characteristics for UVA-NRL-1174-K 8.75-μm diameter, planar four-barrier GaAs/$Al_{0.7}Ga_{0.3}As$ HBV's.

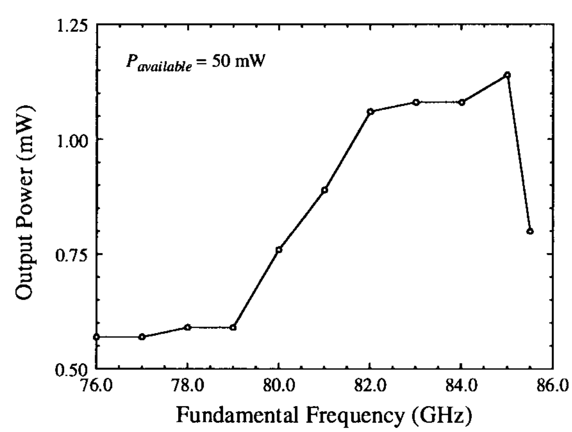


Fig. 6. Output power versus fundamental frequency for the prototype planar four-barrier GaAs/$Al_{0.7}Ga_{0.3}As$ HBV triplers (UVA-NRL-1174-K) at an available power of 50 mW.

input (available) power of 50 mW, the output power versus fundamental frequency for frequencies between 76 and 85.5 GHz is shown in Fig. 6. More than 1 mW of power was generated at fundamental frequencies between approximately 81.5 and 85.25 GHz. At a fundamental frequency of 84 GHz, the output power versus available power is shown in Fig. 7. A maximum output power of greater than 2 mW was generated at 252 GHz with an available power of 80 mW, yielding a peak flange-to-flange tripling efficiency of greater than 2.5%. For historical comparison purposes, the initial whisker-contacted single barrier HBV's of [15] had a maximum output power (tripling efficiency) of approximately 1.25 mW (5%) at an output frequency of 228 GHz (225 GHz). At an output frequency of 252 GHz, the maximum output power was 1 mW with a tripling efficiency of 3%. Subsequent tests using identical whisker-contacted single barrier HBV's in a

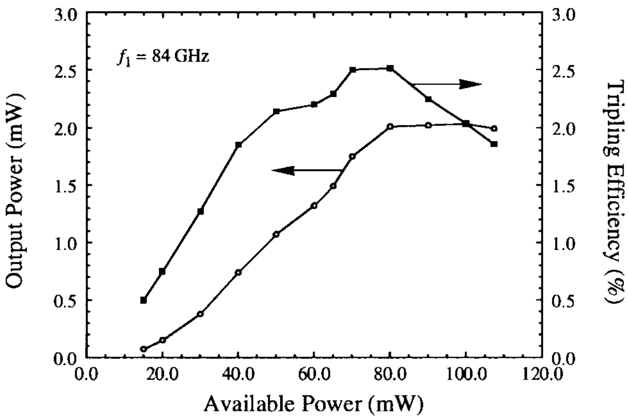


Fig. 7. Output power versus available power for the prototype planar four-barrier GaAs/$Al_{0.7}Ga_{0.3}As$ HBV triplers (UVA-NRL-1174-K) at a fundamental (output) frequency of 84 GHz (252 GHz).

second tripler block yielded a maximum output power (tripling efficiency) of about 0.8 mW (2%) at an output frequency of 192 GHz [16].

V. Conclusion

Planar GaAs/$Al_{0.7}Ga_{0.3}As$ HBV's for frequency tripling from 80 to 240 GHz have been fabricated using a process in which the device surface channel is etched prior to the formation of the contact pad-to-anode air-bridge finger. Formation of the device air-bridge finger after etching the surface channel is facilitated by a trench planarization technique and yields a device with minimal parasitic capacitances. A back-to-back device geometry has been utilized to maximize the symmetry of the MBE-grown epitaxial structure used to fabricate the devices, and the specific contact resistances of the dual ohmic contacts have been minimized by using standard AuGe/Ni/Ti/Au ohmic contacts on an n^+ InAs/$In_{0.0-1.0}Ga_{1.0-0.0}$/AsGaAs epitaxial structure.

Prototype four barrier HBV triplers with nominal 10-μm diameter anodes have been tested in a crossed-waveguide tripler block; as much as 2 mW of power has been generated at 252 GHz with a flange-to-flange tripling efficiency of 2.5%. These devices are the first planar or multibarrier HBV triplers reported and their output powers are nearly double that of previous whisker-contacted single-barrier HBV's. The use of a multiplier block specifically designed for direct triplers is expected to yield improved performance of these devices. Furthermore, significant improvement in the output power and efficiency of these devices is expected with an aggressive redesign of the multibarrier HBV device modulation regions that accounts for velocity saturation phenomena [8].

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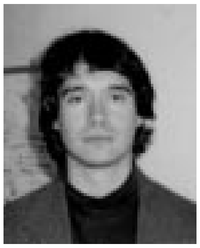

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