DEMONSTRATION OF POWER COMBINING AT W-BAND FROM GaAs/AlAs RESONANT TUNNELLING DIODES

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Abstract

Double barrier resonant tunnelling diodes (DBRTDs) have been fabricated from GaAs/AlAs structures. Oscillation is noted at 75GHz for whisker contacted devices. A modified Kurokawa-Magalhaes combiner circuit has been constructed and with two devices a quadrupling of output power (in comparison with a single device) has been achieced at W-band.

Introduction.

The Double Barrier Resonant Tunnelling Diode (DBRTD) has been claimed as the fastest purely electronic device in existence. In defence of these claims fundamental oscillations at 712GHz have been noted [1] from a DBRTD and although the available power was modest, this result indicates the potential of this device for generating terahertz power.

The DBRTD has been the subject of extensive study over the past ten years [2]. Negative differential resistance in the device arises from the resonant enhancement of the tunnelling current through a quantum-confined region between two atomic-scale barriers. Various material systems have been chosen to realize DBRTD structures: the 712 GHz oscillation result [1] was achieved using an InAs/AlSb structure; at 2GHz, 20mW output power, and 50% dc to rf conversion efficiency, has been measured from AlAs/InGaAs DBRTDs. The proven materials system GaAs/AlAs [3] offers many advantages for the production of DBRTDs which include high interface quality, good uniformity across the wafer and predictable current-voltage characteristics; oscillations from GaAs/AlAs DBRTD devices have been reported up to 412GHz [3]. These advantages accrue from the mature state of GaAs/AlAs molecular beam epitaxy (MBE) growth technology and the resulting layers are compatible with other existing GaAs devices such as monolithic microwave integrated circuits (MMIC).

For DBRTD devices to make any technological impact, it is essential that the power levels generated at high frequencies by these diodes be increased. However, the relatively high efficiency obtained at 2GHz [4] illustrates the potential of these devices when the match between the device and the cavity is optimized; this optimization problem represents the main difficulty with the practical application of these devices at 100GHz and above. At these frequencies the requirements on mechanical tolerances of the cavity and any matching circuits are extreme and approaching the limits of conventional machining capabilities. Electro Discharge Machining (EDM) and the techniques of micro-machining can provide alternatives for realizing these millimetre-wave cavities.

Although the maximum frequency of oscillation of the DBRTD device has been set at several THz [5], in practice this upper limit is reduced by device parasitics such as capacitance and contact resistance. To overcome the limitation of the DBRTD capacitance it is essential to use small ($<10\mu m$) mesa structures. The combination of small device size, necessary for high frequency operation, and the inherent low power of existing DBRTD oscillators is currently a limiting factor in their practical application. One approach for increasing the output power available is to combine the power produced from a number of individual devices; a technique that has been successfully used for IMPATTs and Gunn devices at microwave frequencies [6]. This paper provides the first evidence of successful power combining using DBRTDs at millimeter wave frequencies.

Device Details

Figure 1 shows a GaAs/AlAs DBRTD structure grown by MBE which has been produced specifically for whisker contacting. Figure 2 shows the current-voltage characteristic for this structure; the asymmetry of the characteristic is evident and is a result of the inclusion of a low-doped collector region adjacent to one of the barriers which results in an asymmetric voltage distribution across the device.

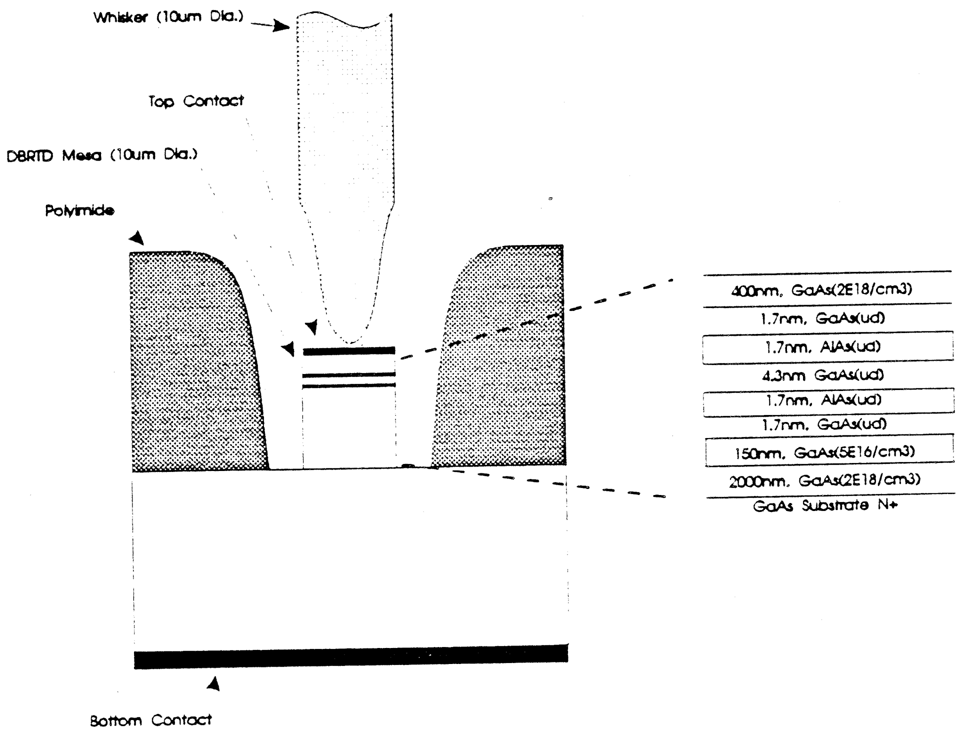

Figure 1 Layer structure and schematic of a DBRTD

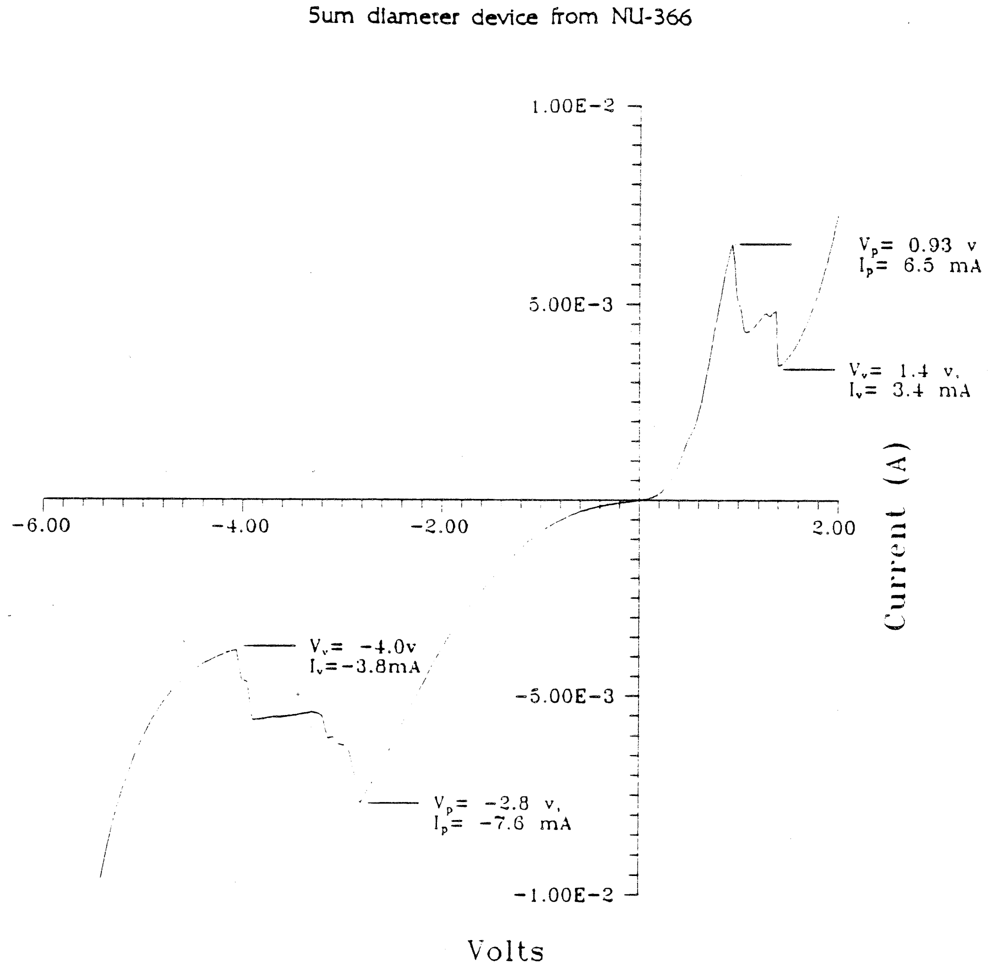

Figure 2 Current versus Voltage for a 5μm diameter device

The purpose of the low-doped region is threefold: it increases the voltage range over which negative differential resistance (NDR) is observed; increases the magnitude of the NDR and also reduces the capacitance per unit area. The first effect results in an increase in the power available; the second improves the ability to extract the power available through improved matching capabilities and the third consideration allows a higher operating frequency. The high capacitance per unit area associated with the older Esaki tunnel diodes [7] was one of their main limitations. The restriction on device size with increasing frequency, noted previously, implies the further difficulty of providing low resistance contacts. At present, contact behaviour can only be optimised through a reduction in the specific contact resistance ($\sim 1 \times 10^{-7} \Omega cm^2$) by using especially highly-doped or indium based layers at the contacts, or by using techniques which separate the contact area from the junction area [8].

Because of their simplicity, whiskers were used to achieve contact between the small area ($<20\mu m^2$) devices and the millimetre-wave circuit. Also, the whisker is thought to act as an antenna for coupling the millimetre-wave power produced in the DBRTD device to an external circuit. A significant drawback of the present whisker contacting process is that it necessitates the use of N^+ substrates and it is suspected that the resulting separation between the device top-contact and the ground plane introduces skin-effect losses which become significant at high millimetre-wave frequencies.

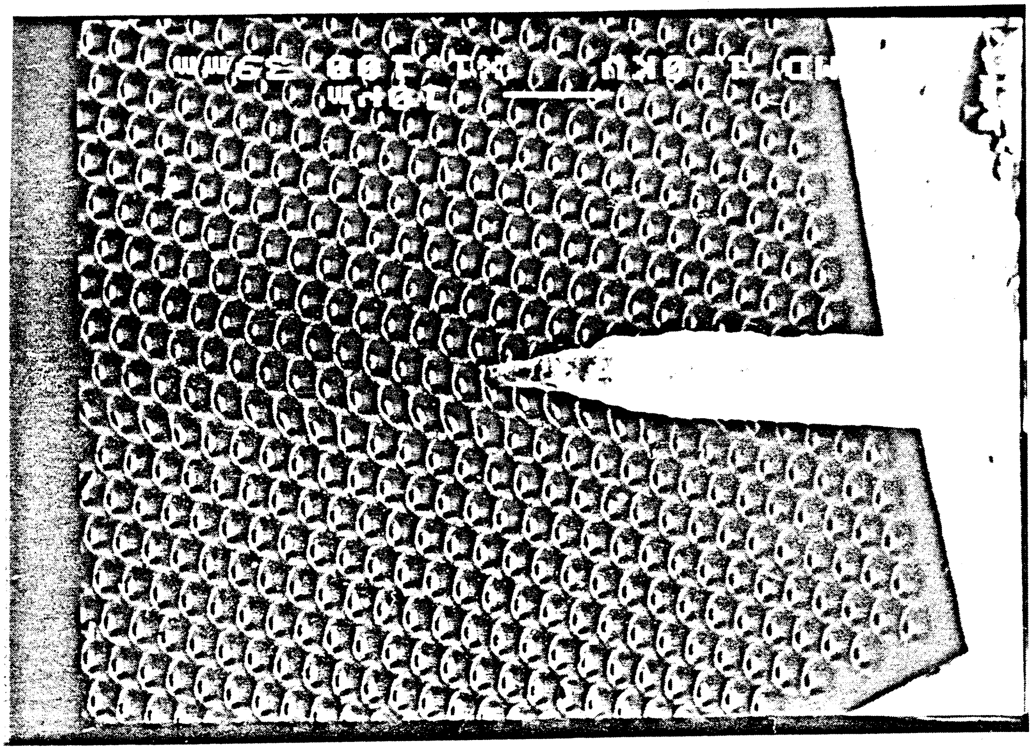

Figure 3 Micrograph of DBRTD during whisker contacting

Figure 3 shows a device in the process of being contacted and Figure 4 shows a typical output spectrum obtained from a whisker-contacted device in a quarter-height waveguide cavity. Reduced height waveguide was chosen to help improve the match with the DBRTD because it has a lower characteristic impedance (approx. 70Ω versus 310Ω for a full height waveguide at 75GHz).

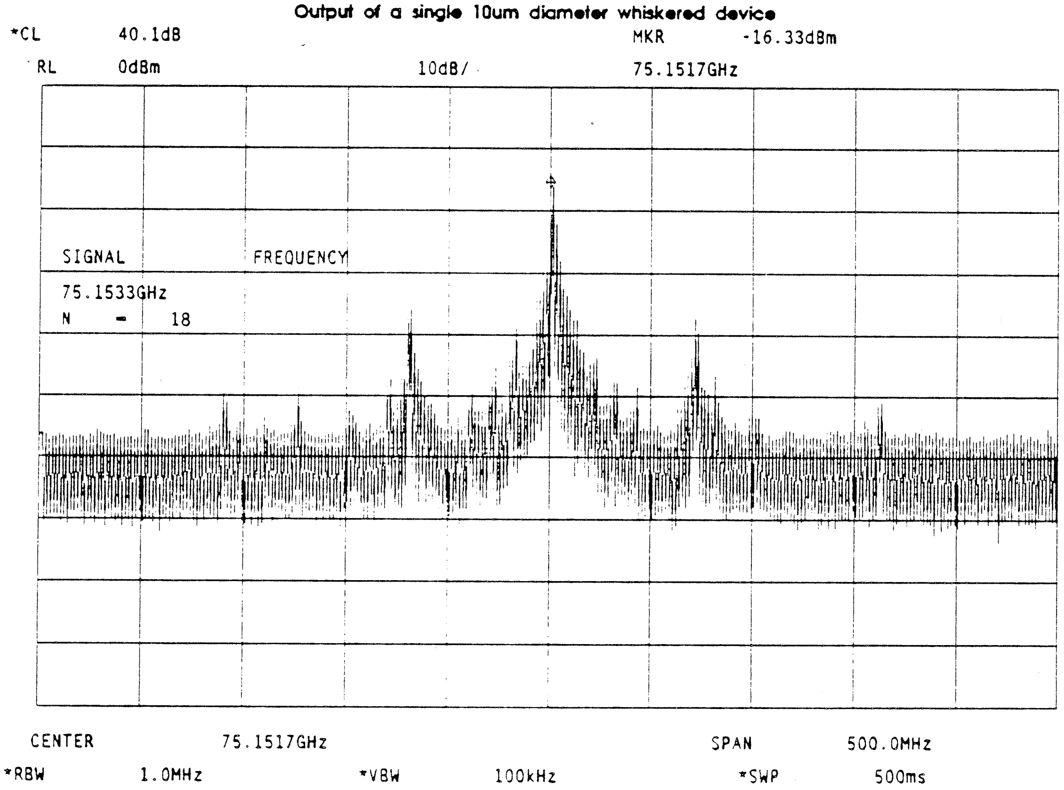

Figure 4 Output spectrum of a 10μm diameter DBRTD

Figure 4 shows a power of 23μW from a 10μm diameter device at 75GHz for a whisker contacted DBRTD. This result was achieved after careful positioning of the device in the cavity and after tuning using a backshort. It is notable that this result compares favourably with the maximum power reported at W-band from a DBRTD device [9].

Power Combining

To compensate for the modest output power of individual DBRTDs various power combining strategies have been investigated. The approach reported on here is a modification of the Kurokawa-Magalhaes combiner [10]. The important modifications are that the devices are mounted in Sharpless-style packages [11] (Figure 5) and the necessary phase separation between devices is achieved by using appropriate length spacers which are themselves simply sections of waveguide. The separation is half the wavelength in the guide at the oscillation frequency.

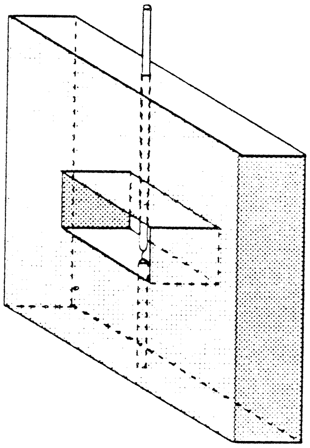

Figure 5 Schematic of a W-band package

The device cavity consists of a section of quarter height W-band waveguide with an array of 10μm dia. DBRTDs on a chip mounted on a pin protruding through the bottom wall of the guide. The whisker consists of a 10μm diameter phosphor-bronze wire 250μm long mounted on an insulated pin protruding through the top wall of the guide. The DBRTDs are placed centrally at the bottom of the waveguide sections which ensures stronger coupling between neighbouring devices compared to the original Kurokawa design. Coherent combining results from the injection locking of two strongly coupled devices oscillating at the same frequencies. Investigation of the electromagnetic environment in the immediate vicinity of the device has been undertaken using the High Frequency Structure Simulator (HFSS) software package from Hewlett Packard. These investigations reveal that the electromagnetic field disturbance is restricted to a region of 500μm around the device which equates to approximately 10% of the wavelength in the guide at this frequency.

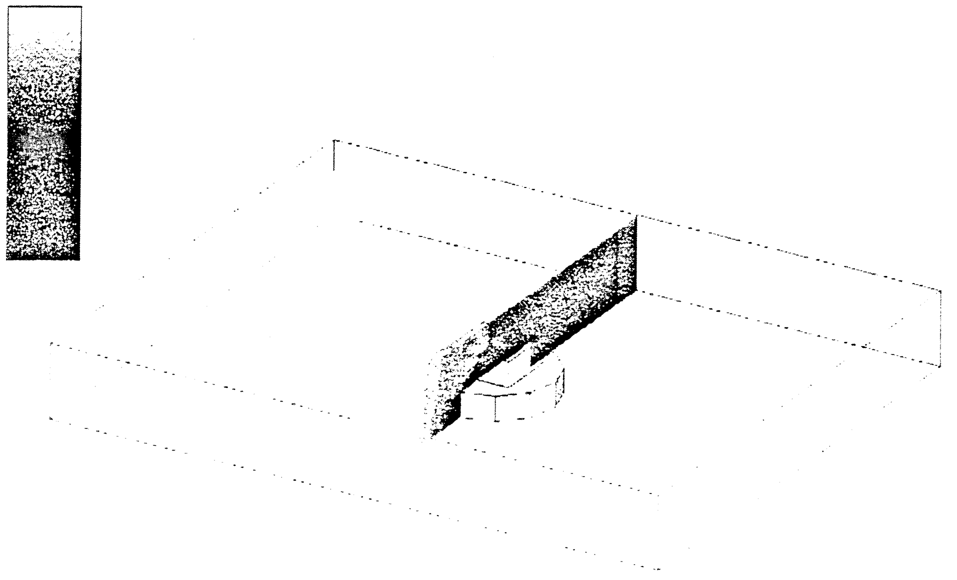

Figure 6 Electric field distribution near DBRTD in reduced height waveguide: lighter areas denote higher fields.

Figure 6 illustrates the results of this simulation. The electromagnetic field modelling reveals the sensitivity of the electric field at the device to its position with respect to the top wall of the waveguide; as a result care was taken to position each device accurately in its cavity to achieve an operating frequency similar to its neighbours.

In the example of the combiner pictured in Figure 7, the oscillation frequencies of adjacent DBRTDs are adjusted by slight variations to the bias of each device. This is possible due to the relatively low "Q" of the cavity afforded by the Sharpless package (as used in the above example). This typically permits the frequency of either DBRTD to be varied by about ± 300MHz for a 200mV variation in bias.

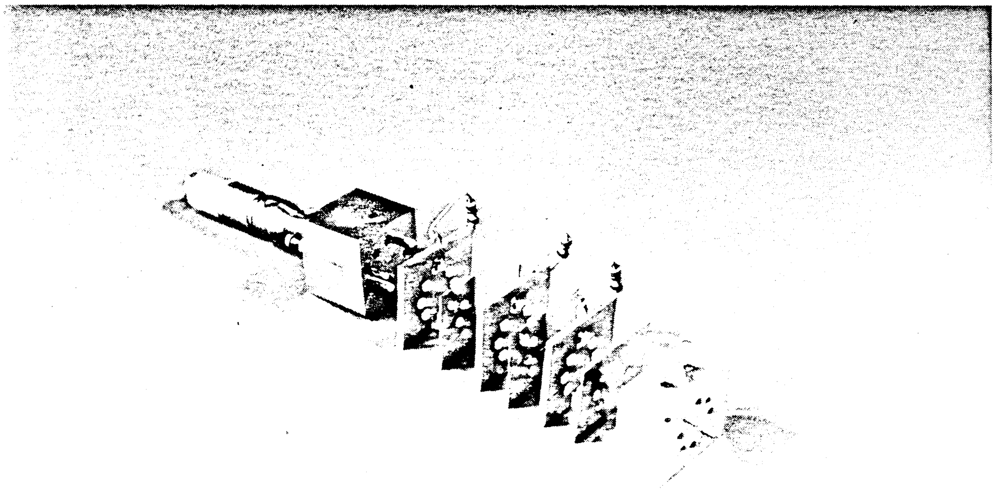

Figure 7 W-band power combiner with devices ready for assembly

Figure 8 shows the output spectra of two DBRTD's before and after combining and shows that the combined output power is quadrupled over that produced by a single device (the unmarked peaks represent alias of the real signals and are artifacts of the process used to acquire the spectra). The extra power produced over and above that of the straightforward addition of the individual device powers is thought to arise from the more favourable impedance seen by either device as a result of the shunting effect of its neighbours.

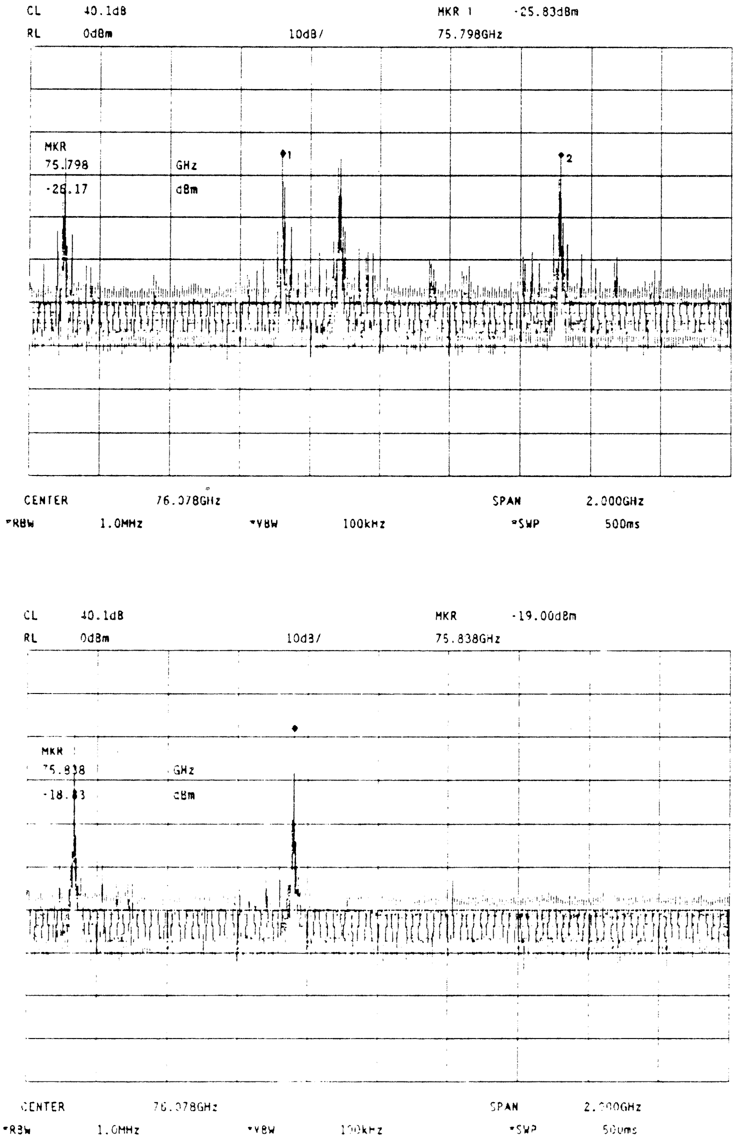

Figure 8 Output spectrum of two DBRTD's before (top) and after combining (bottom).

It is worth noting that the two devices shown in Figure 8 do not produce nearly as much power as the device shown in Figure 4 and this is due to later refinements in the match for this device-cavity combination. Efforts are underway to improve this match still further, and then to combine these improved devices in a similar way to those of Figure 8.

Conclusions

Power combining has been achieved using two DBRTDs and has quadrupled the output power available from a single device. A power of 23µW has been measured for a single device and attempts are being made to combine the output of these improved devices.

In the future, the development of planar devices and circuits should increase the control over matching conditions and further improve the output power of individual devices. This is especially important at higher frequencies such as G-band (140-220GHz) and will involve the integration of devices on stripline and other circuits.

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