Coherent Power Combining of Millimeter Wave Resonant Tunneling Diodes in a Quasi-Optical Resonator

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Abstract

A Fabry-Perot resonator with a grating has been used for coherent power combining of a resonant tunneling diode (RTD) array in the millimeter wave region. Coherent power combining with two RTD's in the resonator has been succesfully observed for the fundamental TEM_{00} resonator mode at the frequency of 75 GHz.

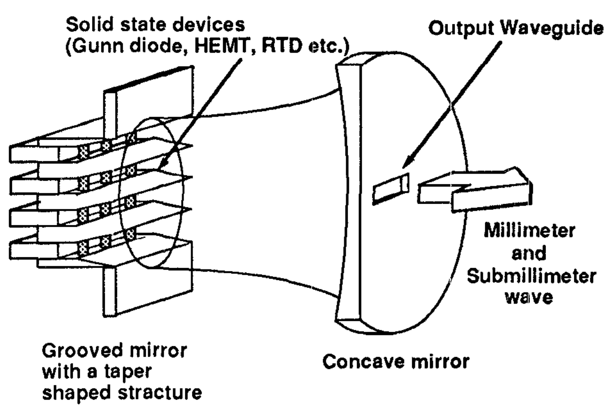

Fig.1 Configuration of the Fabry-Perot resonator with a metallic grating

Introduction

A resonant tunneling diode (RTD) has a negative conductance enough to oscillate at millimeter and submillimeter wave frequencies, but has a low radiation power of only 100 μW or less [1]. In order to overcome this problem, a Fabry-Perot resonator with a metallic grating mounted with an array of RTD's have been developed as a quasi-optical power combiner in millimeter and submillimeter wave frequency regions . Figure 1 shows the configuration of the resonator. The resonator consists of a concave output mirror and a grating (grooved mirror) with solid state devices (Gunn diodes [2][3], HEMT, RTD etc.), and has a high Q-value even in the submillimeter wave frequency region. The grating makes impedance-matching of the resonator to devices easy, and in addition acts as a heat sink and a bias circuit for devices. Coherent power combining of two RTD's in this configuration has been successfully observed for the first time at the frequency of around 75 GHz. In this paper, theoretical and experimental results are reported to show the feasibility of this oscillator with RTD's.

Design of diode structure and DC characteristics

GaAs/AlAs wafers for millimeter wave RTD's have been designed to have negative conductance at the frequencies up to 500 GHz by using Tsu-Esaki's tunneling theory [4] and E.R.Brown's equivalent circuit [1]. Parameters of design are a thickness of AlAs barrier, a width of GaAs quantum well, a doping density of epitaxial layer outside AlAs barriers and a diameter of a diode. Figure 2 shows one of the calculated results for the design of diodes. An operating frequency of a RTD has strong dependence both on a barrier thickness and on a diameter of a diode.

The schematic cross section of the fabricated device for operation at 75GHz is shown in Fig.3. Epitaxial

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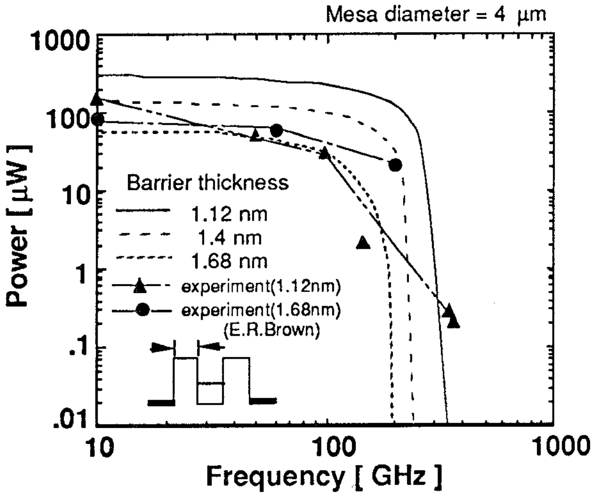

Fig.2 Calculated result of output power vs frequency for RTD for three different barrier thickness

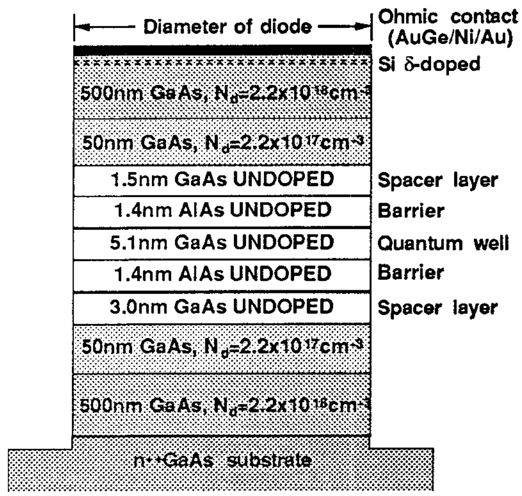

Fig.3 Schematic cross section of fabricated RTD

layers were grown by MBE in the University of Tokyo. The active part of the structure consists of 1.4 nm-thickness AlAs barriers, 5.1 nm-thickness GaAs quantum well, and a doping density of $N_d \approx 2.2 \times 10^{17}$ cm^{-3} for outside the double barrier structure. Si δ-doped layers at top of the diode are used to form ohmic contact. Optimum diameter of the diodes was calculated using the equivalent circuit for oscillation at millimeter wavelengths. According to calculated results, the diodes with mesa structures of different diameters have been fabricated using photolythographic techniques and a reactive ion etching (RIE) with PCl3 gas. Figure 4 shows SEM image of the fabricated RTD with mesa structures of 3μm diameter.

Figure 5 is a typical DC I-V characteristic of the fabricated RTD at the room temperature, showing negative differential resistance (NDR) regions.

Figure 6 shows the measured peak (resonant) tunneling current of the fabricated diodes (1.4 nm-barrier) as a function of diode diameter. The results for the diode with a 2.2 nm-barrier have been also plotted in the Fig. 6. The good agreement between experiments and calculated results shown in Fig. 6 verifies the validity of our design theory for the diodes.

Fig.4 SEM image of fabricated RTD with 3μm diameter

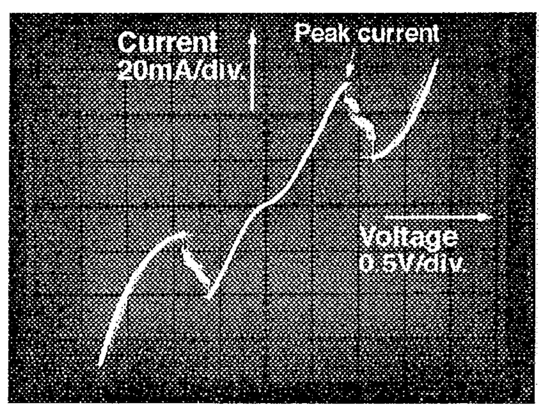

Fig.5 DC I-V characteristics of RTD with 9μm diameter

Resonator configuration and oscillation

Figure 7 shows the configuration of our oscillator with the fabricated RTD's. A tapered structure at front of the grooved mirror was introduced to improve impedance matching between the groove circuit and the free space. The diodes with a diameter of 9 μm were used in our experiment. Each diode was mounted in the groove and contacted with a whisker antenna. The backshort was insulated by a Teflon sheet to feed a bias current to the diodes. The impedance of the circuit can be changed by adjusting a groove height d and a curveture R of the concaved mirror, and determines oscillation frequency. An output power was extaracted through U-band or W-band standard waveguide at the center of the mirror.

For the oscillator with a single RTD, the oscillation frequency tuned with the resonator length L ranges from 49.4 to 49.6 GHz for d = 2 mm and R= 250 mm, 58.9-59.3 GHz for d = 1 mm and R = 250 mm, and 71.8-81.3 GHz for d = 1.0 mm and R = 60 mm. These results were summarized in Table I. Those experimental results show that the fabricated diode has a gain enough to oscillate over a wide frequency range from 49 GHz to 81 GHz, while the calculated maximum oscillation frequency is around 150 GHz for this diode configuration.

Coherent power combining

For coherent power combining of two RTD's, the diodes were mounted in the groove of the Fabry-Perot resonator. The two diodes in parallel were fed a bias by a DC power supply. Figure 8 compares the measured frequency spectrum of a oscillator with one and that of two RTD's. In this experiment the oscillators with d = 1 mm and R = 60 mm have been used. This Figure shows that the output power of the oscillator with two RTD's has increased by about 6 dB compared to that with single RTD, without any increase of the noise level. These experimental results indicate that output power from two RTD's has been coherently combined in the resonator.

Figure 9 shows the measured oscillation frequency of the oscillator with two RTD's as a function of the resonator length. The solid and dashed lines show

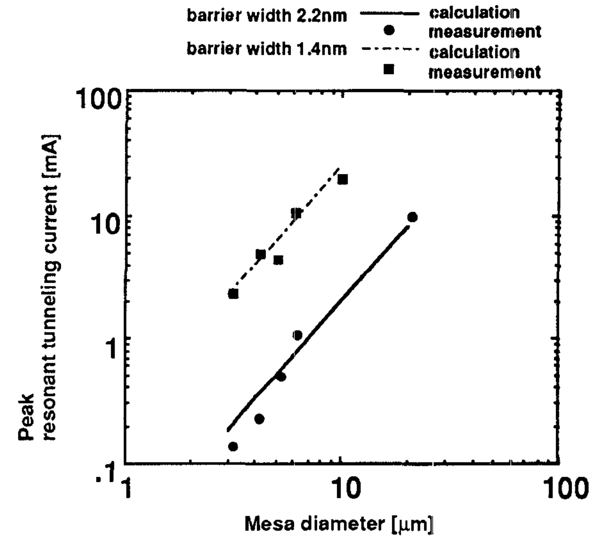

Fig.6. Calculated and measured results for the peak resonant tunneling current of RTD's as a function of a mesa diameter for two different thickness of AlAs barriers.The lines show theoretical peak values of the resonant tunneling cur-

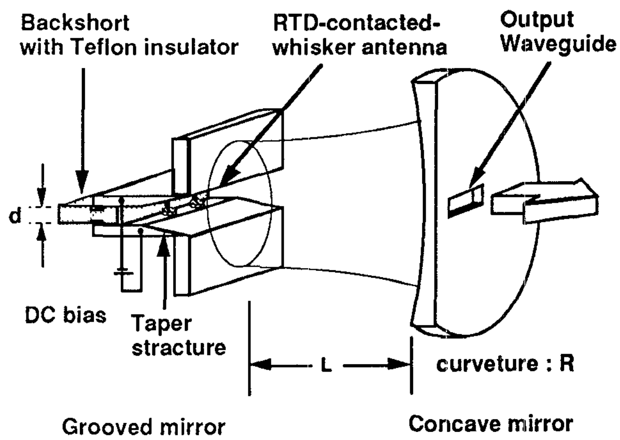

Fig.7 Experimental configuration of the oscillator with RTD's

	Oscillation frequency range
d=2mm R=250mm	49.4 - 49.6 GHz
d=1mm R=250mm	58.9 - 59.3 GHz
d=1mm R=60mm	71.8 - 81.3 GHz

Table I Summary of oscillation results of the different oscillators with single-RTD the resonant frequencies calculated for the TEM_{00}, TEM_{11}, and TEM_{22} resonator modes. In Figure 9, the oscillation frequnecy was changed from 74.6 GHz to 68.7 GHz with the resonator length from 12 mm to 13.3 mm. Those results show that for our configuration with RTD's the oscillation frequency can be changed mechanically more than 8 %.

Conclusion

An open resonator with a metallic grating has been successfully used for coherent power combining of resonant tunneling diodes at up to 75 GHz. Mechanical tuning range of 8 % has been obtained at this frequency range. This configuration can be one of the candidates for practical submillimeter-wave tunable sources with reasonable output power.

Acknowledgments

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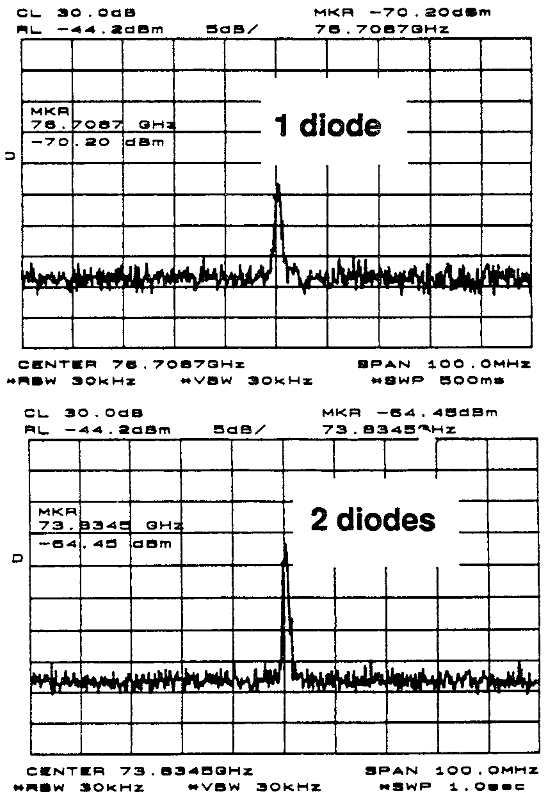

Fig. 8 Measured frequency spectra of the oscillator with one and two RTD's.

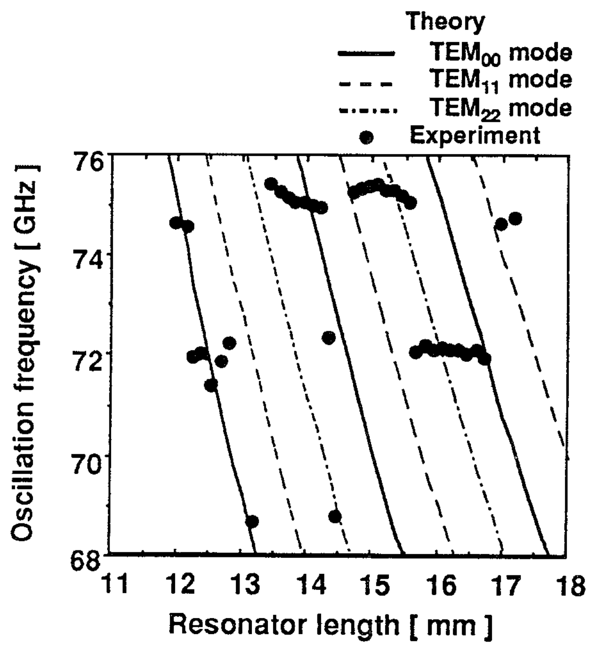

Fig.9 Measured frequency spectra of the oscillator with two RTD's as a function of a resonator length.