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AXIALLY SYMMETRIC FABRY–PEROT POWER COMBINER WITH ACTIVE DEVICES MOUNTED ON BOTH THE MIRRORS

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ABSTRACT

We investigate an axially symmetrical Fabry–Perot power combiner with many more active devices operating in axially symmetric TEM_{01n} mode, which has an excellent feature of uniform device–field coupling required for high power combining efficiency. By numerical calculation using the boundary element method, it was shown that high combining efficiency can be obtained when a circular groove of larger radius is installed on either the plane mirror or the concave mirror. In experiments at X–band, almost perfect power combining of twenty or twenty-four devices mounted on both the mirror was achieved.

INTRODUCTION

Recently, various methods for combining output powers of solid-state active devices have been developed[1, 2]. In millimeter wave frequency range, power combining using a Fabry–Perot resonator is considered effective and several investigations using the fundamental TEM_{00n}-mode have been reported[3–5]. However, as far as the authors know, the power combining efficiency has been relatively low. One of the reasons is supposed to be insufficient device-field coupling and lack of its uniformity. Inadequate coupling of the resonator to an output line can be another reason of low combining efficiency.

In order to resolve these problems, the authors proposed an axially symmetrical Fabry–Perot multiple–device oscillator shown in Fig.1[6]. The oscillator has a plane mirror which has a circular output window and a circular groove mounted with many solid–state devices. When it operates at an axially symmetrical mode, uniform device–field coupling required for high efficiency combining can be realized. Installation of the output window on the plane mirror can give strong coupling of the resonator to the output line because of narrow beam width at the plane mirror. Then the output coupling can be optimized corresponding to the negative conductance of the active devices. In experiments at X–band, almost perfect power combining was attained for the six- and eight-device oscillators. However, for the case of twelve–device structure power combining efficiency reduced because the strength of the device-field coupling decreases[6].

In this paper, in order to increase the number of devices mounted in the oscillator and achieve high power combining efficiency, we study the structure in which a circular groove of larger radius is installed on the concave mirror or the plane mirror. In addition, we investigate the Fabry–Perot oscillator mounted with devices on both the mirrors in order to double the number of devices.

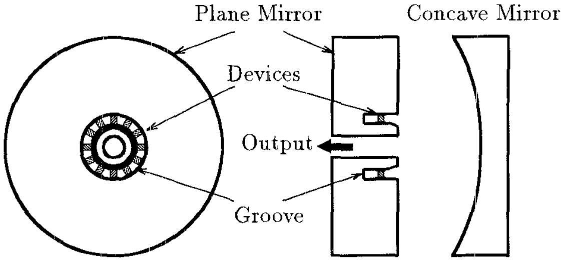

Fig.1 Axially symmetrical Fabry–Perot multiple–device oscillator.

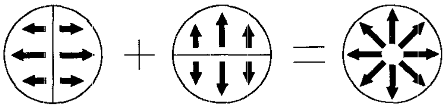

Fig.2 Axially symmetrical TEM_{01n} mode derived by sum of two linear–polarized modes.

STRUCTURE OF OSCILLATOR

We consider the Fabry–Perot oscillator shown in Fig.1 and use an axially symmetrical TEM_{01n} mode shown in Fig.2 as a combining mode. This mode is obtained by combination of two linearly polarized TEM_{01n} mode, one in x-direction and the other in y-direction. Thus electric field of this mode has only radial component of azimuthally uniform magnitude. In order to achieve efficient power combining, every active device should generate the maximum output power cooperatively. This requires the same *rf* device current of the optimum magnitude through all the devices[7], which can be attained by uniform and sufficient device-field coupling. Active devices are mounted at equal spacing in the circular groove on the plane mirror or the concave mirror and are coupled to the axially symmetrical field in the groove.

The coupling of the device to electromagnetic field in the resonator consists of two steps; (A) the coupling of the devices to the groove field, and (B) the coupling of the groove field to the resonator. The uniformity of device–field cou-

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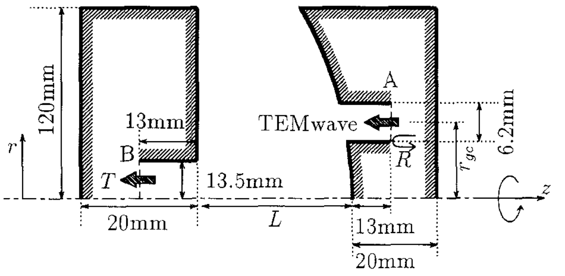


Fig.3 Resonator model for analysis for the case of groove on the concave mirror.

pling is derived naturally because of axial symmetry of both the structure of the oscillator and the electromagnetic field. Empirically in this type oscillator, efficient power combining is caused when it oscillates approximately at the frequency which corresponds to the wavelength equal to twice the spacing between devices[5, 6]. Thus, we use a groove of larger radius for increasing the number of the devices as far as the coupling (B) is strong enough for efficient power combining.

When the devices are mounted on both the mirrors, the device–field coupling for the devices on the plane mirror and the concave mirror should be the same in order to achieve high power combining efficiency. From this viewpoint, when the same number of active devices are mounted in the grooves on both the mirrors, both the grooves should have the same radii at which the couplings of (B) are equal to each other.

The circular output window is installed at the center on the plane mirror and oscillating power is extracted through a circular output waveguide. A propagating mode of the circular waveguide is TM_{01} mode corresponding to the axially symmetrical combining mode.

NUMERICAL CALCULATION

In order to obtain the field coupling between the groove and the output waveguide, we analyzed numerically the field excited by a coaxial TEM field generated by the active devices in the groove as shown in Fig.3. (This figure shows a structure in case that the groove is installed on the concave mirror.) We analyzed numerically using the boundary element method and calculated the reflection coefficient R at an appropriate reference plane (A in Fig.3) in the groove and the transmission coefficient T to a reference plane (B in Fig.3) in the output circular waveguide, together with the stored energy in the resonator. These reference planes are chosen at the positions where all the modes other than the relevant modes sufficiently decay; the relevant modes are coaxial TEM mode for the groove and TM_{01} mode for the output circular waveguide. Assuming that the metal wall is lossless, the diffraction loss D is given by

$$D^2 = 1 - |R|^2 - |T|^2. \tag{1}$$

The ratio η of the transmitted power to the power radiated from the groove is calculated by

$$\eta = \frac{|T|^2}{D^2 + |T|^2}. \tag{2}$$

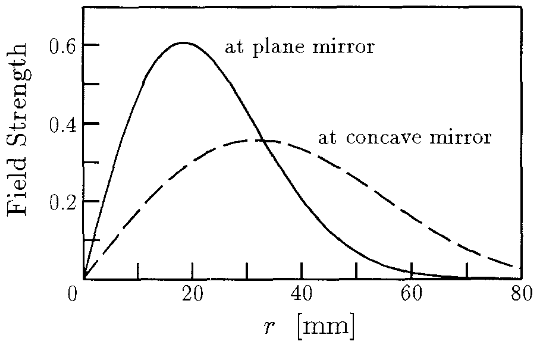
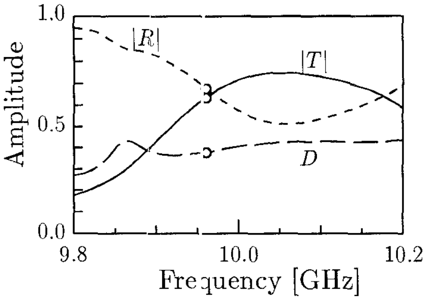


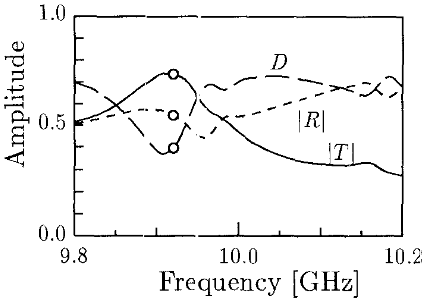
Fig.4 Magnetic field distribution of TEM_{016} mode at mirrors for the case of resonator length 100mm.

This quantity closely relates to the power combining efficiency discussed later.

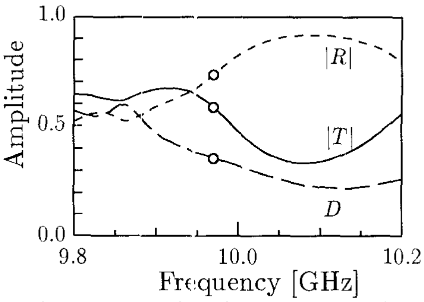
The structural dimensions used in the analysis are indicated in Fig.3 and are the same as those for the experiment later described. Figure 4 shows the magnetic field distribution of TEM_{016} mode at the plane mirror and the concave mirror without a groove and an output window when the radius of curvature of the concave mirror is 150mm and the resonator length L is 100mm. The resonant frequency is equal to 9.91GHz for this case. The radius of the output circular waveguide is chosen as 13.5mm which gives the cutoff frequency of 8.5GHz for TM_{01} mode. The termination of the circular waveguide is assumed reflection-less. The calculated result of the frequency dependence of $|R|$, $|T|$, and D are shown in Fig.5 for three cases when a groove of width 6.2mm exists on either of the mirrors of this resonator: (a) the groove exists on the plane mirror with radius of the groove center $r_{gp} = 22.5$[mm] where the field is almost maximum on the plane mirror, (b) the groove exists on the concave mirror with radius of the groove center $r_{gc} = 34.0$[mm] where the field is almost maximum on the concave mirror and (c) the groove exists on the plane mirror with $r_{gp} = 34.0$[mm] where the magnitude of the field is almost equal to the case (b) as shown in Fig.4. Small circles in these figures denote the resonance point where the stored energy is maximum. The values of the power transmission ratio η at the resonant frequency can be calculated from Fig.5; they are 0.74, 0.78, and 0.73, respectively for three cases. However, as the resonator length increases, the power transmission ratio η decreases because the diffraction loss is increased. Thus, when the resonator length is short, it is seen that high combining efficiency can be obtained even if the field at the position of the groove mounted with devices is not maximum. The value of η for cases (b) and (c) are almost equal to that for case (a) which gives sufficient coupling between the groove and the output waveguide. Then, high combining efficiency is expected when grooves are installed on both the mirrors with the same radii as the cases (b) and (c).



(a) case of groove on the plane mirror with r_{gp} = 22.5[mm]. (power transmission ratio $\eta = 0.74$.)



(b) case of groove on the concave mirror with r_{gc} = 34.0[mm]. ($\eta = 0.78$.)



(c) case of groove on the plane mirror with r_{gp} = 34.0[mm]. ($\eta = 0.73$.)

Fig.5 Frequency dependence of reflection $|R|$, transmission $|T|$, and diffraction loss D for the case of resonator length 100mm.

EXPERIMENT

Experiments were carried out at X-band for twelve, twenty, and twenty-four Gunn diodes oscillators. Figure 6 shows the structure of the oscillator with the same structural dimensions as for the numerical analysis. Twelve diodes were mounted on the concave mirror, while eight or twelve diodes were mounted on the plane mirror. When either of the mirrors was mounted with diodes, the groove was not installed on the other mirror. The groove centers have a radius r_{gp} of 22.5mm or 34mm on the plane mirror, and a radius r_{gc} of 34mm on the concave mirror. The depth of the groove was adjusted by a short plunger for output power maximum. In order to alleviate the discontinuity in impedance at the groove opening, a tapered transition was provided. For the adjustment of the coupling of the resonator to the output waveguide, a circular window was prepared at the waveguide opening. The circular waveguide was converted to a rectangular waveguide.

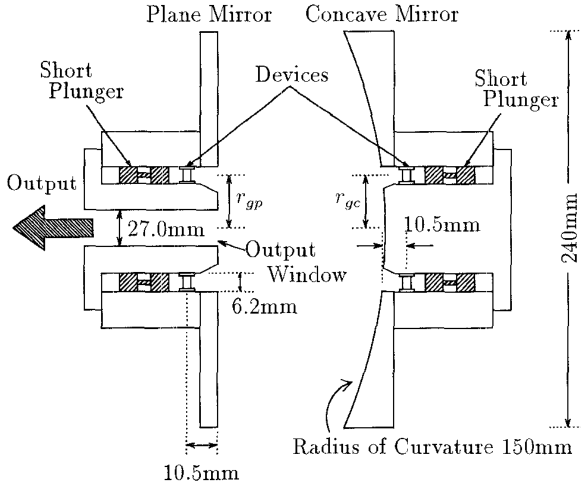


Fig.6 Oscillator structure for experiment.

Figure 7 shows a typical measured variation in oscillation frequency and output power with the resonator length when both of the grooves on the plane mirror (r_{gp} = 34[mm]) and on the concave mirror (r_{gc} = 34[mm]) were each mounted with twelve diodes. In Fig.7(a), the theoretical resonant frequency is also plotted. Compared with the theoretical frequency, it is considered that the oscillator operated at TEM_{01n} mode. High output power was obtained stably even if the resonator length increased.

The measured maximum combining efficiencies for various cases are listed up in Table 1, where the power combining efficiency is defined as the ratio of the output of a multiple-device oscillator to the sum of the maximum output powers of each device when they are measured in a usual waveguide cavity. Then combining efficiency was not sufficiently high when the groove on the plane mirror had small radius which gave the spacing between devices smaller than half of the wavelength. However, high combining efficiency was obtained[1] when the groove of large radius was installed on the plane mirror or on the concave mirror, because the coupling of the devices to the field in the groove is strong due to enough spacing between devices. When both the mirrors were mounted with diodes, almost perfect power combining was attained.

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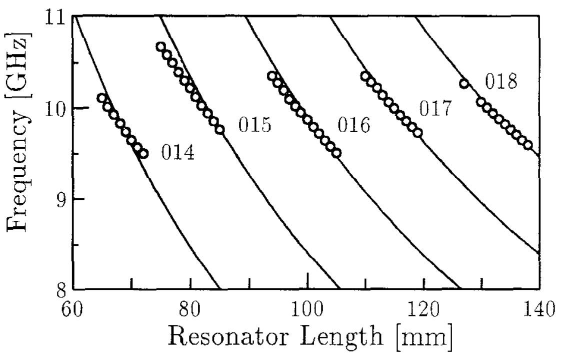
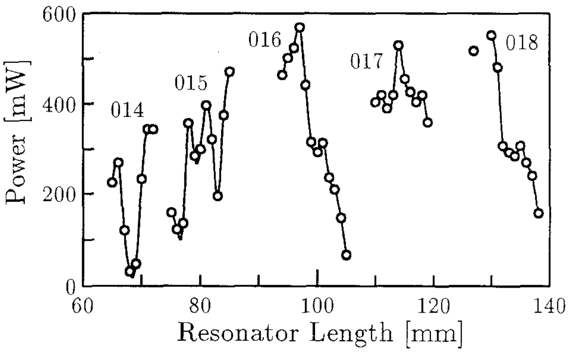
[1] In a usual waveguide cavity single-device oscillator, only less than about 80% of the power generated by the active device can be extracted to the output waveguide; this estimation can be obtained using measured external and internal Q values of the cavity. This is one of the main reasons why power combining efficiency often exceed 100% in experiments. As another important factor, multiple-device oscillators are advantageous in power combining efficiency because the resonator loss is shared by the many active devices[7].

Table 1 Measured maximum combining efficiencies. (— means that the groove is not installed on the mirror.)

radius of groove center on plain mirror r_{gp} (mm)	22.5	34	—	22.5	34
number of diodes on plain mirror	12	12	—	8	12
radius of groove center on concave mirror r_{gc} (mm)	—	—	34	34	34
number of diodes on concave mirror	—	—	12	12	12
resonator length L (mm)	108	98	96.7	99	97
mode number	017	016	016	016	016
oscillation frequency (GHz)	10.80	10.07	10.10	10.04	10.08
maximum efficiency (%)	87.8	91.5	94.5	105.2	100.5



(a) Oscillation frequency



(b) Output power

Fig.7 Experimental result when both mirrors were mounted with twelve diodes and $r_{gp} = r_{gc} = 34$[mm].

CONCLUSION

We investigated axially symmetrical Fabry–Perot oscillators which have circular grooves mounted with active devices on the plane mirror or/and the concave mirror in order to combine the output powers of many more devices. The essential features of the oscillator presented in this paper are as follows. By using the axially symmetrical TEM_{01n} mode, uniform device–field coupling required for high combining efficiency can be realized. The coupling of the resonator to the output line can be strong by installing the output window on the plane mirror. Active devices can be mounted on the concave mirror due to axial symmetry of the structure. Then, the number of the devices can be increased easily by mounting devices on both the mirrors. By numerical calculation using the boundary element method, it was shown that high combining efficiency is expected when the circular groove of larger radius is installed on either the concave mirror or the plane mirror. By experiments at X-band, power combining efficiency as high as 90% was attained for the case twelve devices on either of the mirrors and almost perfect power combining was accomplished for the case of mounting twenty or twenty-four devices on both the mirrors. Power combining in millimeter-wave frequency range is a future subject.

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