# Axially symmetrical Fabry-Perot oscillator with multiple devices inserted in dielectric substrate

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# AXIALLY SYMMETRICAL FABRY–PEROT OSCILLATOR WITH MULTIPLE DEVICES INSERTED IN DIELECTRIC SUBSTRATE

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## ABSTRACT

We investigate an axially symmetrical Fabry–Perot oscillator with active devices inserted in a dielectric substrate for power combining of many more devices in microwave and millimeter wave frequency range. Empirically in this oscillator, efficient power combining can be done when it oscillates approximately at the frequency which corresponds to the wavelength equal to twice the spacing between devices. The wavelength in the dielectric is shorter than in free space, so we tried to insert the devices in the dielectric substrate in order to increase the number of the devices. By measuring the oscillation frequency of the oscillator with sixteen devices at X–band, we confirmed that the spacing between devices was about a half wavelength in the dielectric. We achieved almost perfect power combining of sixteen devices.

## 1. 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. 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 in all the devices[6], which can be attained by uniform and sufficient device-field coupling. Inadequate coupling of the resonator to an output waveguide 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[7]. 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 shown in Fig.2, 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-, eight-, and twelve-device oscillators[7] [8]. Empirically in this type oscillator, efficient power combining is done when it oscillates approximately at the frequency which corresponds to the wavelength equal to twice the spacing between devices[5] [7] [8]. This yields a limitation on increasing the number of the devices. 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 the active devices are inserted in a dielectric substrate on the plane mirror.

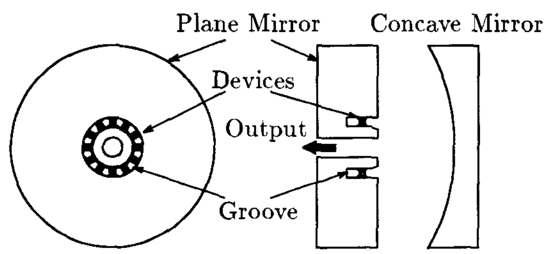



Fig.1 Axially symmetrical Fabry– Perot multiple–device oscillator[7].

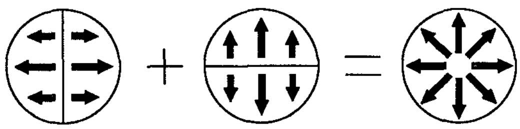


Fig.2 Axially symmetrical $TEM_{01n}$ mode derived by sum of two linear-polarized modes.

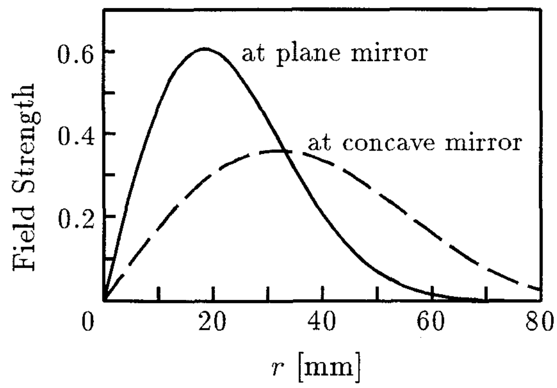



Fig.3 Magnetic field distribution of $TEM_{016}$ mode at mirrors for the case of resonator length 100mm.

## 2. INCREASING OF THE NUMBER OF DEVICES

We consider the Fabry–Perot oscillator which consists of a plane mirror and a concave mirror. Active devices are located at equal spacing on a circle of radius $r_d$ on the plane mirror. Figure 1 shows the Fabry–Perot oscillator which we proposed in our previous study[7]. The axially symmetrical $TEM_{01n}$ mode in Fig.2 used as a combining 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. Active devices are mounted at equal spacing in the circular groove on the plane mirror and are coupled to the axially symmetrical field in the groove.

Figure 3 shows the magnetic field distribution of $TEM_{016}$ mode at the plane mirror and the concave mirror with neither a groove nor 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.

When the radius $r_d$ is equal to 22.5mm and the number of the devices is eight, the spacing between devices is 17.7mm corresponding to half wavelength at 10GHz and almost perfect power combining was achieved[7]. For twelve devices case, when the devices were located on a larger circle of radius $r_d$ =34[mm] where the spacing between devices is 17.8mm, high combining efficiency was obtained with short resonator length. However, when the resonator length increases, efficiency reduces because the field at $r = r_d$ becomes weak compared with the maximum value on the plane mirror and the diffraction loss increases[8]. It is considered that the combining efficiency decreases if the larger radius $r_d$ is used in order to combine powers of many more devices.

The wavelength in a dielectric is inversely proportional to the square root of the dielectric constant and shorter than in free space, so the real spacing between devices corresponding to half wavelength in the dielectric at the oscillation frequency can be reduced. Therefore, many more devices can be mounted with Fabry–Perot oscillator without degrading combining efficiency on the case of the radius $r_d$ at which the field is almost maximum on the mirror.

## 3. EXPERIMENT

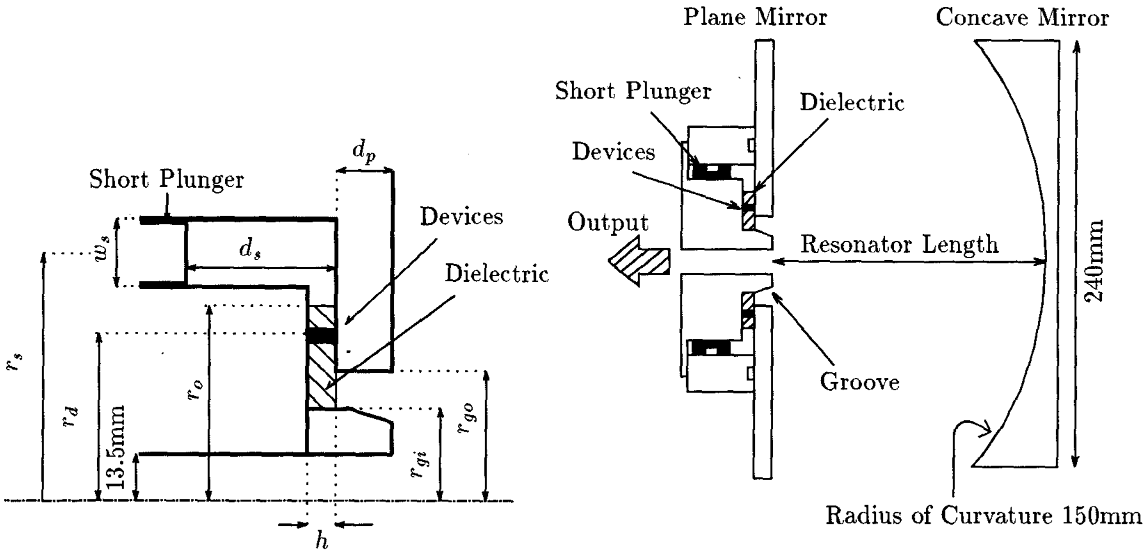
An experiment was carried out at X-band for sixteen Gunn diodes oscillator. Figure 4 shows the structure of the oscillator. Both the radius of the plane mirror and that of the concave mirror are equal to 120mm. A radius of curvature of the concave mirror is equal to 150mm. The diodes are inserted in a dielectric ring on the circle of radius $r_d$=29[mm]. The dielectric ring with an inner radius $r_{gi}$ of 22.9mm and an outer radius $r_o$ of 36.5mm is composed of Rogers Duroid 5870 substrate with a thickness $h$ of 3.17mm and dielectric constant of 2.33. The electromagnetic wave generated from diodes propagates radially to $+r$ and $-r$ directions. The wave propagating to $-r$ excites Fabry–Perot resonator through a coaxial groove with an outer radius $r_{go}$ of 26.5mm and a depth $d_p$ of 4mm. In order to alleviate the discontinuity in impedance at the groove opening, a tapered transition was provided.

The wave propagating to $+r$ is converted from TEM mode of a radial line filled with dielectric to TEM mode of a coaxial line with width $w_s$ at $r_s$ =43[mm] through a radial line filled with air. Figure 5 shows an equivalent circuit of converting part from the radial line to the coaxial line. $Z_L$ is a characteristic impedance of the coaxial line and is given by

$$Z_L = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\log\frac{2r_s + w_s}{2r_s - w_s}.$$

$Z_{0a}(r)$ and $Z_{0d}(r)$ denote the characteristic impedance of the radial line filled with the air and the dielectric, respectively and are given by

$$Z_{0a}(r) = \frac{h}{2\pi r}\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{jH_0^{(2)}(kr)}{H_1^{(2)}(kr)}$$




(a) structure of part mounted with devices (b) Entire structure

Fig.4 Oscillator structure for experiment in which sixteen diodes are inserted in dielectric substrate.

$$Z_{0d}(r) = \frac{h}{2\pi r}\sqrt{\frac{\mu_0}{\varepsilon_r\varepsilon_0}}\frac{jH_0^{(2)}(k\sqrt{\varepsilon_r}r)}{H_1^{(2)}(k\sqrt{\varepsilon_r}r)}$$

where $k$ is propagation constant in free space, $\varepsilon_r$ is dielectric constant , and $H_0^{(2)}(r)$ and $H_1^{(2)}(r)$ are second kind of Hankel functions. If $Z_s$ which is impedance looking forward to the coaxial line at $r = r_s$ is equal to $Z_{0d}(r_o)$, reflection do not take place on the converting part and the wave is reflected by only a short plunger in the coaxial line. Therefore, output power maximum can be obtained by adjusting the position of the short plunger. $Z_s$ is expressed as follows:

$$Z_s = |Z_{0a}(r_o)|\frac{Z_L\cos\alpha - j|Z_{0a}(r_s)|\sin\alpha}{|Z_{0a}(r_s)|\cos\beta - jZ_L\sin\beta}$$

where

$$\alpha = \theta(kr_o) - \psi(kr_s)$$
$$\beta = \psi(kr_o) - \theta(kr_s)$$
$$\theta(kr) = \arg\{H_0^{(1)}(kr)\}$$
$$\psi(kr) = \arg\{jH_1^{(1)}(kr)\}.$$

Figure 6 shows the variation of $Z_s$ versus $r_s$ for the case of frequency 10GHz, $\varepsilon_r = 2.33$, $h = 3.17$[mm], $w_s = 5$[mm], and $r_o = 36.5$[mm]. From this result, when $r_s$=43[mm], $Z_s$ is nearly equal to $Z_{0d}(r_o)$.

Figure 7 shows a typical measured variation of the oscillation frequency and the output power with the resonator length. In Fig.7(a), the theoretical resonant frequency is also plotted. Compared with the theoretical frequency, it is considered that the oscillator operates

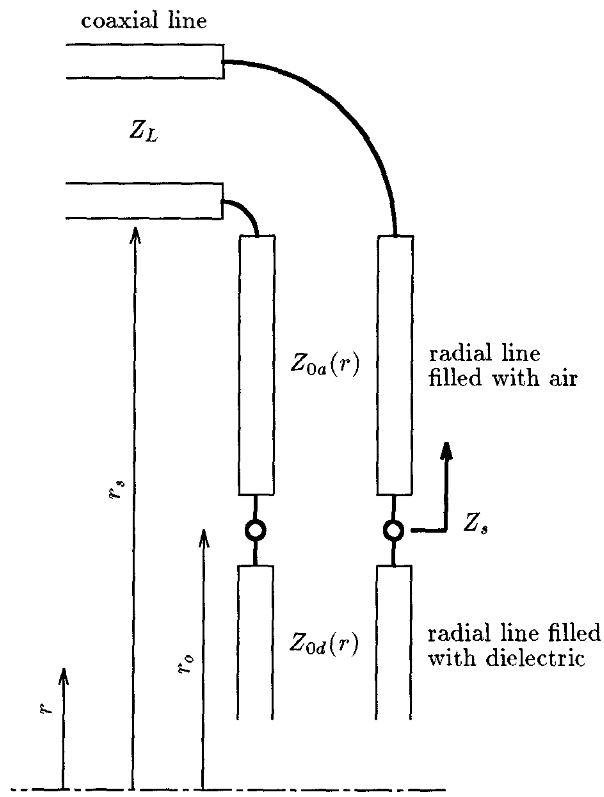



Fig.5 Equivalent circuit of converting part from radial line to coaxial line

at $TEM_{01n}$ mode. The oscillation frequency was about 10GHz, so the spacing between devices was nearly equal to half of the wavelength in the dielectric substrate.

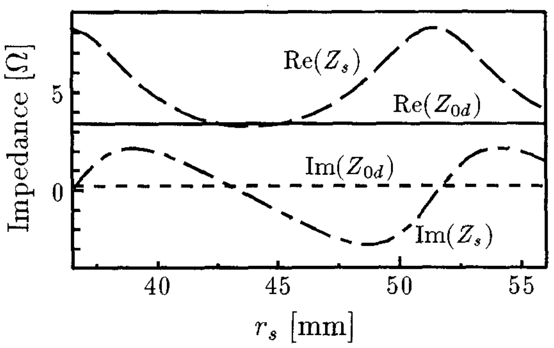



Fig.6 Variation of $Z_s$ versus $r_s$ for the case of frequency 10GHz, $\varepsilon_r$ = 2.33, $h$ = 3.17[mm], $w_s$ = 5[mm], and $r_o$ = 36.5[mm].

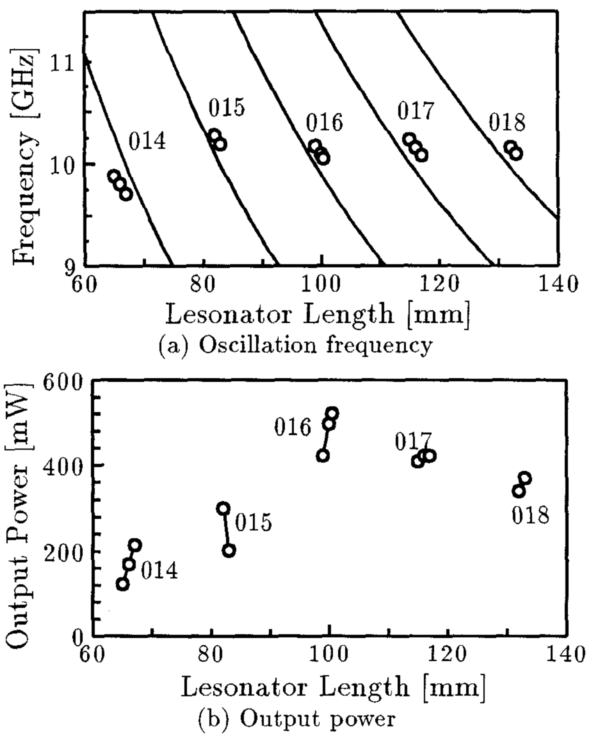



Fig.7 Experimental result

Thus the effect of inserting the active devices in the dielectric was confirmed. Defining the combining efficiency as the ratio of the output power of the multiple–device oscillator to the sum of the maximum output powers of each device when they are measured in a usual waveguide cavity, the maximum value obtained was 107% when the resonator length was equal to 101mm.

## 4. CONCLUSION

We investigated the axially symmetrical Fabry–Perot oscillator with active devices inserted in the dielectric substrate on the plane mirror. The wavelength in the dielectric is inversely proportional to the square root of the dielectric constant, so the real spacing between devices corresponding to a half of the wavelength in the dielectric at the oscillation frequency can be reduced. Therefore, the higher dielectric constant of the substrate is, the more the number of the devices can be without degrading the combining efficiency. By experiments at X–band, the usefulness of the dielectric was confirmed and almost perfect power combining of sixteen devices was achieved. The future subject is power combining of more many devices and in higher frequency range.

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