Gaussian-Beam Open Resonator with Highly Reflective Circular Coupling Regions

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Abstract—**A high-Q open resonator with new-type quasi-optical coupling regions is described. The resonator consists of a pair of spherical mirrors, on each of which a highly reflective, partially transparent circular region is fabricated with a diameter larger than several wavelengths. The signal is coupled in and out as a Gaussian beam by means of these regions. Both very weak coupling and very efficient mode conversion are simultaneously achieved. This results in a Q factor over 2×10^5 and a high signal-to-noise ratio at 105.9 GHz. The Q factor of the open resonator can be varied by rotating the output mirror to change the angle between the directions of the conducting stripes on the two mirrors.**

I. Introduction

The open resonator, or Fabry-Perot resonator, with one or two concave spherical mirrors is usually used as a high-Q resonator at millimeter-wave frequencies. The use of mirrors with large apertures makes diffractive loss negligibly small [1]. High-Q open resonators have been investigated for precision measurement of low-absorbing materials [2]. The modes of the resonator are explained by using the scalar Gaussian beam theory [3].

In millimeter-wave open resonators, the electromagnetic energy is usually coupled in and out through a small hole in the mirror connected to a waveguide. The diameter of the hole is smaller than one wavelength. However, for this type of resonators, fine coupling adjustment that is needed to attain a high Q factor is always a serious problem. Attainment of Q factors over 10^5 results in large insertion losses of the order of 25–30 dB [4] due to strong diffraction at the coupling hole.

A quasi-optical coupling method, which can also be used in the submillimeter-wave region, has been used to reduce this diffraction [5]. In this method, the excitation beam was coupled in through a quartz mirror with a metal thin-film layer of 0.1% transmittance. However, use of such a small transmittance results in a large insertion loss due to the absorption caused by the metal resistance. To avoid such absorption, an attempt has been made to use metallic meshes as coupling regions in a square cavity [6].

In order to couple the exciting Gaussian beam directly with the open resonator, we have developed a new quasi-optical coupling method [7] that simultaneously achieves both very weak coupling and very efficient mode conversion.

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II. Weak Coupling for High Q Open Resonator

A. Conventional Methods

Fig. 1(a) shows a conventional waveguide-coupled millimeter-wave open resonator. It consists of a pair of spherical mirrors, each of which is connected to a waveguide via a coupling hole. However, it is extremely difficult to control the Q factor, especially at high Q, because it is impossible to control the coupling strength under weak coupling conditions due to the difficulty of precise fabrication of the hole. The other important factor is mode conversion efficiency between the feeder and the resonator. In general, when the apertures of the mirrors are large enough to make diffractive loss negligibly small, the loaded Q factor, Q_L, is given by

$$\frac{1}{Q_L} = \frac{1}{Q_o} + \frac{1}{Q_{C1}} + \frac{1}{Q_{C2}}, \tag{1}$$

where Q_o is the unloaded Q factor due only to the ohmic loss of the mirror surface, Q_{C1} and Q_{C2} are Q factors due to coupling losses by the input and output mirrors, respectively. Coupling coefficients, β_1 and β_2, for input and output, respectively, can be defined by

$$\beta_1 = Q_o/Q_{C1}, \qquad \beta_2 = Q_o/Q_{C2}. \tag{2}$$

Using (2), (1) can be expressed by

$$Q_o = (1 + \beta_1 + \beta_2)Q_L = (1 + 2\beta)Q_L, \tag{3}$$

where both coefficients are assumed to be equal. In waveguide-coupled millimeter-wave open resonators, values of Q_L over 10^5 have been reported. The Q_o is calculated using the literature value of the resistivity of the metal, ρ, in the following relation:

$$Q_o = \frac{D}{2}\sqrt{\frac{\pi\mu_o f}{\rho}}, \tag{4}$$

where D is the resonator length, μ_o is the permeability of vacuum, and f is the frequency. By substituting appropriate values of Q_L and Q_o into (3), β is estimated to more than 0.5. In closed cavities mode conversion efficiency is approximately unity, and in general, the transmittance at resonance, τ, is given by

$$\tau = \frac{4\beta^2}{(1 + 2\beta)^2}, \tag{5}$$

and it takes values of 0.25, 0.34, 0.44, when $\beta = 0.5, 0.7, 1$, respectively. However, when using a waveguide-coupled open

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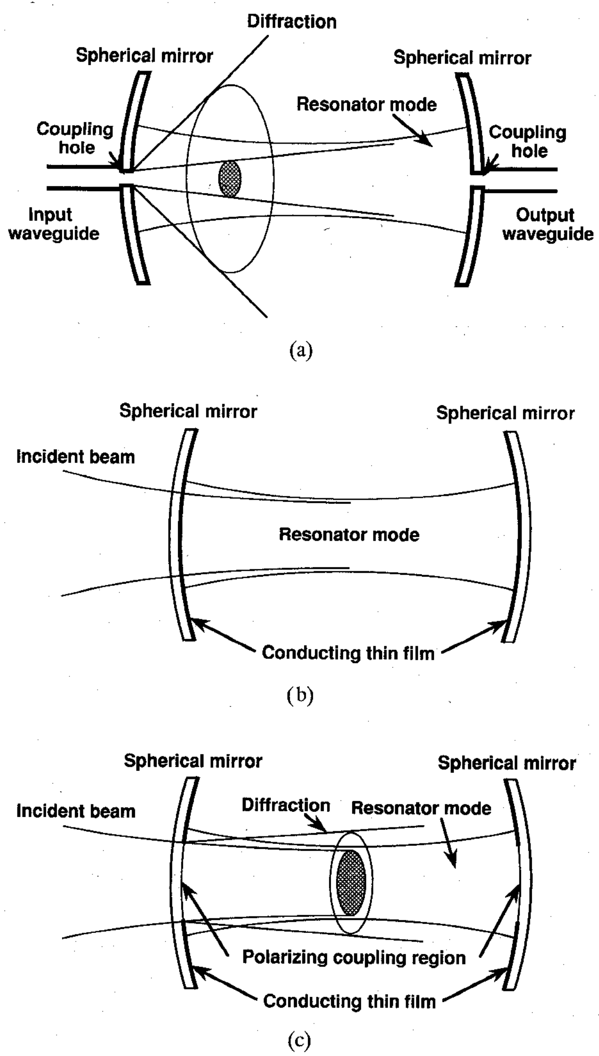


Fig. 1. (a) Conventional waveguide-coupled millimeter-wave open resonators. Each waveguide is connected to the spherical mirror via a coupling hole. The mode conversion is illustrated. (b) Quasi-optically coupled open resonator using partially-transparent conducting thin films. (c) Open resonator consisting of a pair of spherical mirrors with highly reflective coupling regions. Diffraction at the coupling region is small. The exciting beam is efficiently converted into Gaussian mode in the resonator.

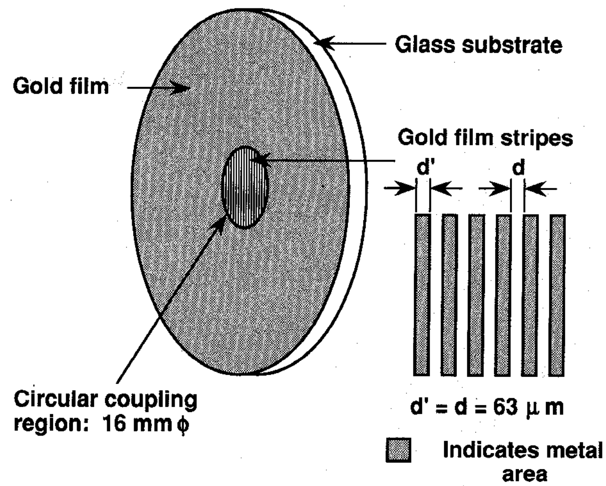


Fig. 2. Schematic diagram of a fabricated spherical mirror.

resonator with Q_L of over 10^5, the measured transmittance at resonance is in the order of 0.001–0.01 [4], and (5) is invalid in this case. This is because the diffraction at a coupling hole is so strong that the major part of the signal power coupled through the hole is diffused over a wide angle inside the resonator, and only a very small part can contribute to the Gaussian resonant mode, as illustrated in Fig. 1(a).

Fig. 1(b) shows a resonator in which quasi-optical coupling is achieved by using partially-transparent conducting thin films over the whole area of the spherical substrates. The transmittance of a single reflecting mirror, T, the absorption and scatter loss on a single pass through one mirror, A, the reflectivity of the mirrors, R, are related as follows:

$$A + R + T = 1. \tag{6}$$

The power transmittance at resonance, τ, of an open resonator with two reflecting mirrors is given by

$$\tau = (1 - A/(1 - R))^2. \tag{7}$$

Substituting for R in this formula by using (6), τ is also expressed by

$$\tau = (T/(A + T))^2. \tag{8}$$

It is difficult to control τ precisely by varying the film thickness. Moreover, attainment of such a small transmittance results in a large absorption due to the metal resistance, so $T/(A + T)$ is very small. The requirement for high reflectivity coupled with low absorption loss is met by using metallic grids or meshes. Fabry–Perot interferometers for use at submillimeter wavelengths are reviewed in [8]. However, plane mirrors were used for the parallel-plane resonator, which cannot attain an extremely high Q factor.

B. A New Quasi-Optical Coupling Method

When a resonator consists of spherical mirrors with metallic-mesh coupling regions fabricated on each mirror, as shown in Fig. 1(c), it is possible to adjust the transmittance without diffraction loss by designing grid parameters [7]. We have fabricated highly reflective, partially transparent mirrors, by reproducible fine processing with controllable and reproducible high Q factors. Fig. 2 shows the schematic of the mirror. In addition, due to a large coupling region, which is several wavelengths in diameter, the diffraction at the coupling region is small and most of the signal power contributes to the Gaussian resonant mode, resulting in a high efficient mode conversion when excited by an approximately Gaussian beam. Fig. 1(c) shows how efficiently the incident beam is converted into the resonator mode.

Moreover, when the mesh pattern is a polarizer composed of conducting stripes (Fig. 2), using the arrangement in Fig. 1(c), it is possible to finely adjust the high Q factor of the resonator by rotating the output mirror to vary the angle between the directions of the conducting stripes of the two mirrors.

Fig. 3 shows the theoretical transmittance of the polarizer for the electromagnetic wave polarized in the direction of the metal stripes. Calculations were performed using the formulae in [9] under the condition that the thickness and resistance of the metal stripes are negligible and the incident beam is a plane wave. The transmittance of the circular region can be designed

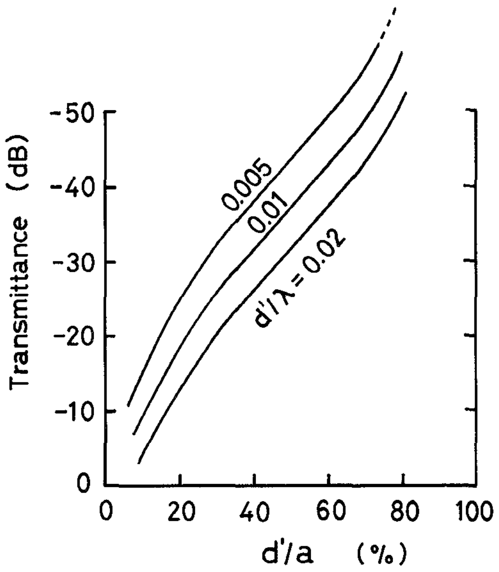


Fig. 3. Theoretical transmittance of the polarizer for the electromagnetic wave polarized in the direction of the metal stripes. We used the formulae in [9] for the calculations assuming that the thickness and resistivity of the metal were negligible and the incident beam was a plane wave. λ is the wavelength, and $a = d + d'$.

between $\sim 10^{-3}$ and $\sim 10^{-5}$ by way of the grid parameters, resulting that Q_{C1} and Q_{C2} are controllable. In our mirrors, both the metal width, d', and the gap width, d, were designed as 63 μm, corresponding to $d'/a = 0.5$ and $d'/\lambda = 0.021$ for 100 GHz, where $a = d + d'$.

III. Experiment

A. Fabrication of Spherical Mirrors

Spherical mirrors were made with sputtered gold film on optically polished 80-mm diameter concave glass substrates with radius of curvature of 200 mm. Film thickness was 1.5 μm, which is several skin depths at 100 GHz. The stripe pattern was formed by using photolithography and dry-etching. The coupling region was designed as 8 mm in radius, which is almost half the beam radius of Gaussian beam (usually expressed by w) on the spherical mirror of a symmetric resonator with a resonator length of 280 mm.

B. Measurement

Fig. 4 is a block diagram of the 100-GHz-band open-resonator setup. Spherical mirrors were configured so that the optical axes coincided. The input mirror was set so that the direction of the stripes coincided with that of the polarization of the incident beam. It was supported on a linear-translation unit in order to find resonant points by moving along the axis. The output mirror could be rotated and its angle was detected by an encoder.

A highly stable and spectrally pure signal source is required for measurement with a high Q open resonator. The signal source was an electrically tunable Gunn oscillator that was phase locked to a synthesizer over the range of ± 100 MHz

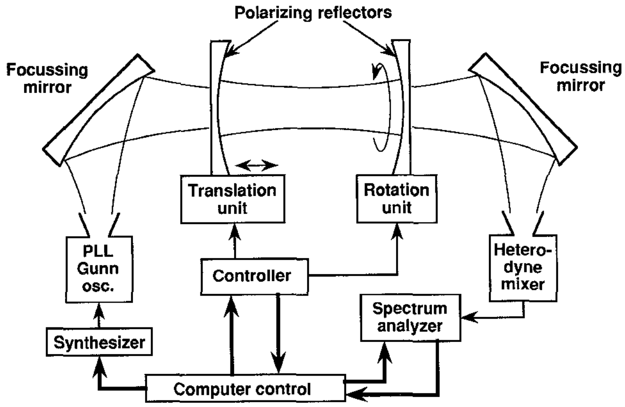


Fig. 4. Block diagram of the 100-GHz-band open-resonator setup.

with frequency stability better than 1 part in 10^9. The transmitted signal was processed by a mixer and a spectrum analyzer.

Resonator characteristics were measured by precisely scanning the frequency around 105.9 GHz with a resonator length fixed at 280 mm. The relation of the loaded Q factor with the rotational angle, θ, between the directions of metal stripes on the two mirrors is shown in Fig. 5. When θ was zero, Q_L became 2.4×10^5, while Q_L fell to 5×10^4 at $\theta = 15°$. The diameter of the coupling region was $1/\sqrt{2}$ times the beam diameter (the distance between points in the cross section of a beam where the power density is $1/e$ of the peak value) on the spherical surface, and approximately half the total reflected power was reflected by the coupling region. Therefore, the dependence on θ should be weaker than the case if the conducting stripes cover the whole mirror surface. The broken line in the figure indicates the limit value of Q_L, or the unloaded Q factor, Q_o, which is due only to the ohmic loss of the mirror surface. Using $\rho = 2.2\ \mu\Omega$ cm in (4) for the resistivity of gold at room temperature, it was calculated as 6.1×10^5.

Moreover, a signal-to-noise ratio of more than 60 dB was easily obtained with a 10 mW output from the oscillator.

IV. Discussion

The experimentally obtained Q factor reached 40% of the theoretical limit when using gold reflecting mirrors. The grid parameters, d and d', can be easily controlled by using thin-film microlithography. Therefore, by reducing the gap width, it is possible to make Q_L higher. This quasi-optical coupling method is also potentially applicable to resonators in the submillimeter-wave range. The resistivity of the high-purity noble metals (Cu, Ag, Au) is reduced by a factor of $10^3 - 10^4$ by cooling to less than 15 K [10]. Using (4), we can estimate that Q_o of $10^7 - 10^8$ will be achieved in the 100 GHz band. Moreover, if high-quality superconducting thin films are used at temperatures much lower than T_c, Q_o over 10^8 will be possible. Then, Q_L of the same order is essentially achieved by designing the coupling Q factors by way of the grid parameters, according to the value of Q_o.

This resonator will be a powerful tool for precision dielectric measurement of low-loss materials. It will overcome difficulties encountered in previous experiments and will enable

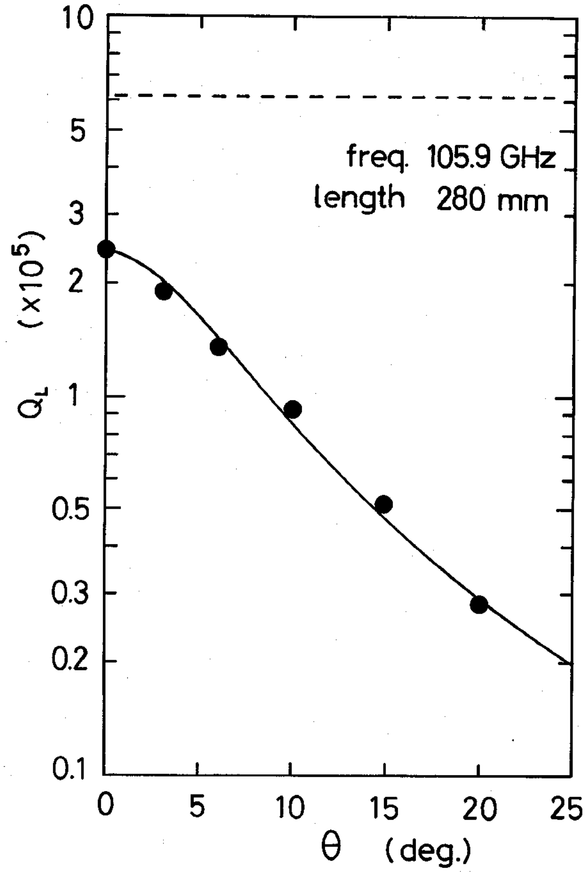


Fig. 5. Measured loaded Q factor, Q_L, versus the angle, θ, between the directions of the metal stripes on the two spherical mirrors. Closed circles indicate experimental data and the solid curve shows the result calculated by considering that the reflected power from the polarizing region and that from the surrounding region are equal.

high-sensitivity detection. If this coupling method is applied to reflection-type measurement, reflected power will be sensitive to resonance and a resonant curve with a high signal-to-noise ratio will be obtained [11]. This resonator will be convenient for precision measurement of highly reflective samples, such as superconductors.

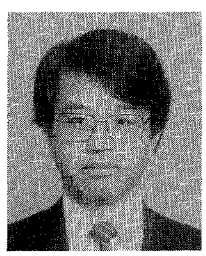
It is also applicable to quasi-optical filters and wavelength meters. Parallel-plane open resonators are usually used for such applications. However, they have the disadvantages that the diffraction loss is large for a finite beam diameter and that maintenance of a small diffraction loss above the short millimeter-wave frequency range requires increasingly precise alignment of the parallel plane mirrors. These disadvantages will be overcome by using our quasi-optical coupling method. Moreover, by rotating one of the mirrors, variable bandwidth will be obtained in quasi-optical filters and variable finesse in wavelength meters. Other important application is a quasi-optical oscillator [12]. Power can be extracted as a Gaussian-beam rather than in the conventional waveguide mode.

V. Conclusion

A high-Q open resonator has been developed with highly reflective, partially transparent coupling regions which are larger than several wavelengths. The signal is coupled in and out as a Gaussian beam by means of these regions. An experiment carried out at 105.9 GHz using symmetric configuration attained a Q factor of over 2×10^5. Thus, fine control of weak coupling is possible for millimeter-waves. Moreover, the high signal-to-noise ratio obtained in this measurement system verified that the resonator mode excitation efficiency was greatly improved over that of conventional waveguide-coupled resonators.

References

[1] G. D. Boyd and J. P. Gorden, "Confocal multimode resonator for millimeter through optical wavelength masers," *Bell Syst. Tech. J.,* 1962, vol. 40, pp. 489–508.
[2] A. L. Cullen, "Millimeter-wave open-resonator techniques," ch. 4 in *Infrared and Millimeter-Waves,* vol. 10, K. J. Button Ed., New York: Academic Press, 1983, pp. 233–281.
[3] H. Kogelnik and T. Li, "Laser beams and resonators," *Proc. IEEE,* vol. 54, no. 10, pp. 1312–1329, Oct. 1966.
[4] R. N. Clarke and C. B. Rosenberg, "Fabry–Perot and open resonators at microwave and millimeter wave frequencies, 2–300 GHz," *J. Phys. E: Sci. Instrum.,* vol. 15, pp. 9–24, 1982.
[5] M. Tsuji, H. Shigesawa and K. Takiyama, "Open-resonator method for submillimeter wave dielectric measurements," in *9th Int. Conf. Infrared and Millimeter Waves: Conf. Dig.* 1984, pp. 372–373.
[6] K. A. Lee and M. A. Frerking, "Experimental results of a high Q quasioptical reflection cavity," *Int. J. Infrared and Millimeter Waves,* vol. 10, no. 7, pp. 789–802, 1989.
[7] T. Matsui and K. Araki, United States Patent no. 5 012 212.
[8] E. A. M Baker and B. Walker, "Fabry-Perot interferometers for use at submillimetre wavelengths," *J. Phys. E: Sci. Instrum.,* vol. 15, pp. 25–32, 1982.
[9] N. Marcuvitz, *Waveguide Handbook.* New York: McGraw-Hill, 1951, pp. 280–285.
[10] D. E. Gray, *American Institute of Physics Handbook.* New York: McGraw-Hill 1972, Sec. 9, pp. 38–56.
[11] T. Matsui, M. Kiyokawa and B. Komiyama, "An open resonator for testing surface resistivity of superconductor films and metallic samples at 100–120 GHz," in *13th Int. Conf. on Infrared and Millimeter Waves Conf. Dig.* SPIE 1039, pp. 199–200, 1988.
[12] M. Kiyokawa and T. Matsui, "A new quasi-optical oscillator with Gaussian output beam," to be submitted.



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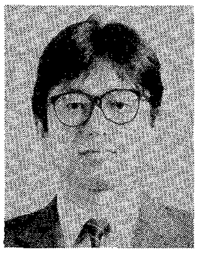

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