Short Papers

Cold Tests of Quasi-Optical Gyrotron Resonators

R. P. Fischer, T. A. Hargreaves, and A. W. Fliflet

Abstract—**Cold tests are performed on quasi-optical gyrotron resonators at frequencies near 94 and 120 GHz to measure cavity Q. The separation between the resonator mirrors is varied between 0.15 and 0.35 m, with measured quality factors ranging from 10 000 to 100 000. Good agreement is obtained between the measured data and values calculated from scalar diffraction theory. The effect of misaligning the mirrors is also examined experimentally.**

I. Introduction

The quasi-optical gyrotron (QOG) is currently under development as an efficient, high-power source of millimeter-wave radiation [1], [2]. The quasi-optical resonator comprises a pair of spherical mirrors separated by many radiation wavelengths. The QOG operates in a series of TEM_{00l} modes, where the axial mode index $l > 100$ for CW relevant configurations. Higher order transverse modes can suffer from large diffraction losses owing to the finite size of the mirrors. The diffraction of the TEM_{00l} modes around one or both of the mirrors is collected as output, with typical round-trip diffraction losses from less than one to several percent. This output coupling sensitively depends upon the mirror size, radius of curvature, and separation. For a given pair of symmetric mirrors, output coupling is increased by increasing the separation between the mirrors.

The quality factor (Q) of a resonator is an important parameter which describes how well the cavity stores energy and it is closely related to the output coupling. The Q for a Fabry–Perot-type resonator can be very large. Quality factors of the order of 100 000 are typical for resonators used in recent experiments [2]. Since the balance between ohmic losses and diffraction is very important in the QOG, a detailed experimental study is called for.

Fabry–Perot-type resonators have been used extensively to measure the microwave properties of solids, liquids, and gases [3]. For permittivity and loss measurements, the design goal is to achieve as large a Q as possible. This is accomplished by making the mirrors large so that diffraction losses for the fundamental transverse mode are negligible. Energy is typically coupled into the cavity through coupling holes or a dielectric beam splitter.

Cold tests of gyrotron cavities are difficult to perform in practice. Most cold-test schemes involve drilling coupling holes into the cavity walls [4], which can perturb the cavity mode severely. It is also difficult to couple efficiently to the mode of interest, which is frequently a high-order mode. Woskoboinikow *et al.* [5] radiated their conventional gyrotron cavities in the far field and analyzed the reflected signal. This technique has the advantage of being nondestructive, so that the hot test cavity may be used for the cold test. It is difficult to test a QOG resonator using this method because little energy is coupled into the resonator mode.

The QOG operates in the fundamental Gaussian mode, which allows for a straightforward method to couple to the proper mode in the resonator. This study uses the technique of Perrenoud *et al.* [6], where a small hole is used to couple energy into the resonator and diffracted power is collected with a standard gain horn for output. This approach has a distinct advantage in that there is no background radiation pattern on the oscilloscope trace, which increases the accuracy of the measurement. The size of the hole can be chosen so that it has a small effect on the quality factor of the resonator. The majority of the measurements in this paper concern the variation of Q with mirror separation for various resonators. The theoretical model accurately predicts the behavior of these resonators as the separation is varied. This is in contrast to other work which indicated poor agreement between theory and experiment over a wide range of mirror separations [6]. The effect of misaligning the mirrors is also examined experimentally.

II. Quasi-Optical Resonators

The Q of a Fabry–Perot-type resonator can be written

$$Q = \frac{4\pi L}{\lambda f_L} \tag{1}$$

where L is the separation between mirrors, λ is the free-space wavelength, and f_L is the fractional round-trip loss of the radiation in the cavity. In practice, this loss factor includes ohmic losses, diffraction losses, and losses caused by coupling holes. These are the three loss mechanisms which are important in this study. The total Q of the resonator can be expressed as

$$\frac{1}{Q} = \frac{1}{Q_\Omega} + \frac{1}{Q_{d.c}} \tag{2}$$

where Q_Ω is the ohmic Q, and $Q_{d.c}$ is the Q from diffraction and coupling losses. The ohmic Q is calculated using the formula [7]

$$Q_\Omega = \frac{L}{2}(f\pi\mu_0\sigma)^{1/2}. \tag{3}$$

In this expression, f is the frequency, μ_0 is the permeability of free space, and σ is the conductivity of the mirrors. Silver- and gold-plated mirrors are used in the cold tests, with conductivities of 6.15×10^7 and 4.5×10^7 S/m, respectively. The ohmic Q increases linearly with separation and has a small effect on the total Q for output coupling greater than a few percent.

The diffraction/coupling Q is calculated separately from the ohmic Q. This is accomplished with a computer code[1] which is

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[1]Code written by K. Yoshioka, with a formulation similar to that found in [8].

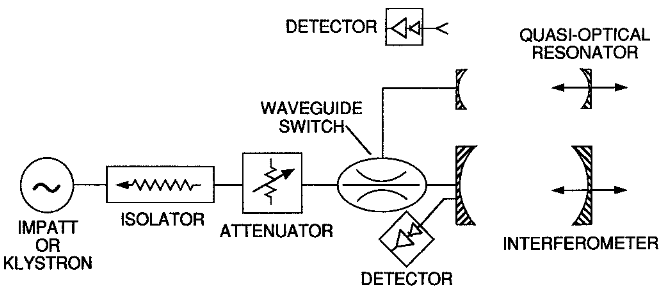

Fig. 1. Schematic diagram of the cold-test apparatus.

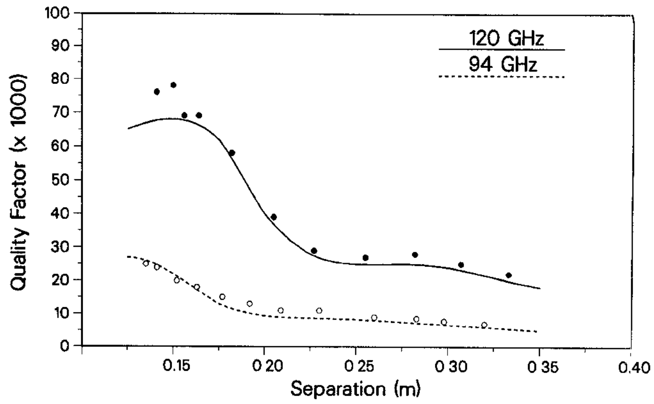

Fig. 2. Measured (discrete points) and theoretical values (curves) of resonator Q versus mirror separation for 45-mm-diameter mirrors.

based on the scalar formulation of Huygens's principle. The program solves the integral equations of the open resonator as a matrix eigenvalue problem, yielding the eigenfunctions. Inputs to the code include the wavelength of the radiation, the mirror radius, the radius of curvature of the mirrors, the separation between the mirrors, the dimensions of a coupling hole, and a parameter which specifies the mesh size. Outputs from the code include $Q_{d,c}$, the balance between Q_d and Q_c, and the electric field distribution along the surface of each mirror for the TEM_{00} and TEM_{10} modes. Other modes may also be analyzed. The solution converges rapidly for output couplings above 1%.

A chief obstacle to performing cold tests of millimeter-wave resonators is coupling power into the cavity without perturbing the quality factor substantially. In this study, a small coupling hole is drilled through the center of one mirror. The size of the hole is chosen to minimize degradation of Q while coupling a sufficient amount of power into the cavity. The radius of the coupling hole is 0.38 mm. For mirror separations greater than 0.20 m, there is practically no difference between the quality factors of the resonator with and without the coupling hole. This cold test cavity should be a good model for the QOG experiment, where the separation can be varied between 0.20 and 0.28 m. This resonator lies well within the confocal instability point at 0.387 m separation and the concentric stability limit at 0.774 m separation. Below 0.20 m separation, any change in the round-trip losses results in a large change in the total Q, caused by the small output coupling. In this regime, all three loss mechanisms are important and the diffraction code loses accuracy.

III. Cold Test Apparatus

A schematic diagram of the experimental setup is shown in Fig. 1, and is similar to that adopted by Perrenoud *et al.* [6]. The entire arrangement is located on an optical table, with the quasi-optical resonator mirrors mounted on 152-mm-diameter optical mounts which can be translated by hand on a rail.

A 0.76-mm-diameter coupling hole pierces the left mirror. It is counterbored from behind, leaving a 0.15 to 0.25 mm wall. A WR-8 waveguide is inserted from the back of the coupling mirror for input, while a standard gain horn intercepts a small amount of the diffracted signal for output. In practice, the pickup horn may be placed behind either mirror.

Two millimeter-wave sources are used for the measurements. The first is a 94 GHz IMPATT which produces 20 mW of power. Its frequency is swept by applying a 1 V ramp to the FM port. The second source is a 120 GHz reflex klystron with a power output of several milliwatts. It is also swept with a low-voltage ramp, which is amplified in the klystron power supply/modulator and applied to the reflector. It is desirable to have a linear frequency sweep versus time for the millimeter-wave source. This allows for direct measurement of the full width at half maximum (FWHM) of the transmission resonance from the oscilloscope with no corrections. Typical frequency sweeps are 20 MHz and are linear over the range of interest for most resonators.

A detector/amplifier which has a sensitivity of 50 V/mW is used to observe the small signals collected by the radiation pickup. The detector and its power supply are shielded, which reduces the noise on the oscilloscope to 0.1 mV. Typical resonances observed on the oscilloscope are 1–2 mV. The horizontal trace is calibrated using the interferometer shown in Fig. 1. The interferometer comprises two 152-mm-diameter mirrors and has a Q of approximately 70000. The separation can be varied between 0.32 and 0.43 m, with fine adjustments facilitated by a micrometer graduated to 0.00254 mm. The interferometer would not be required if the quasi-optical resonator mirrors were mounted with a precision micrometer.

The resonator mirrors are made of oxygen-free, high-conductivity copper. They are machined, polished, and then plated with either silver or gold. The surface finish is $\lambda/20$ for $\lambda = 10$ μm. Thus, surface scattering of millimeter waves should be negligible. The mirrors have a 0.5 mm bevel at the mirror's edge, which decreases the effective diameter by 1.0 mm.

A unique feature of the cold test arrangement is that the resonator mirrors are aligned with an HeNe laser. The incident beam defines the axis of the resonator so that the mirror angle can be optimized by aligning the reflected and incident beams. The coupling hole is used to full advantage by passing the beam through the hole for centering and alignment. The resonator mirrors can be rapidly aligned to better than a tenth of a degree.

IV. Results

Fig. 2 shows measured and calculated values of Q versus separation for a resonator with 45-mm-diameter mirrors. The coupling hole is 0.76 mm in diameter and the radius of curvature is 0.387 m for each of the mirrors used in the cold tests. The data are taken at frequencies of 94 and 120 GHz, with good agreement between data and theory. For a frequency of 120 GHz, the measured values are somewhat higher than predicted at closer separations, where the coupling hole becomes important and the numerical results lose accuracy. At 94 GHz,

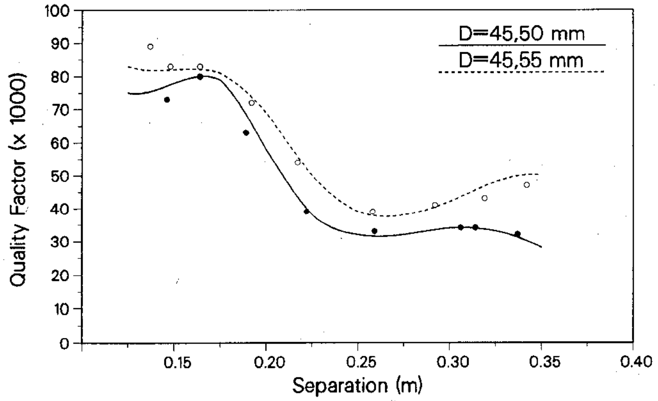

Fig. 3. Measured (discrete points) and theoretical values (curves) of Q versus mirror separation for two asymmetric resonators at 120 GHz.

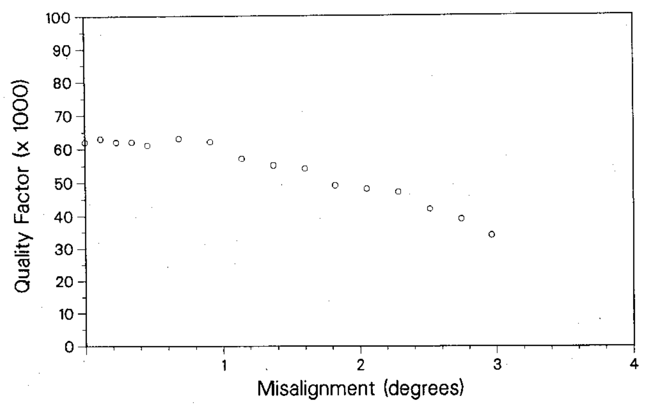

Fig. 4. Q versus mirror misalignment for an asymmetric resonator at 94 GHz and mirror diameters of 50 and 55 mm.

the values for Q are much lower owing to increased diffraction losses at the longer wavelength. A Q of 7000 corresponds to a round-trip transmission coefficient of 18% at a separation of 0.26 m for 94 GHz radiation.

The present QOG utilizes a symmetric cavity; the mirrors are identical. Future configurations may include asymmetric resonators which couple power from one side only. Fig. 3 shows measured and calculated Q's for slightly asymmetric cavities. The solid curve corresponds to resonator mirrors 45 and 50 mm in diameter, while the dashed curve indicates results for mirrors 45 and 55 mm in diameter. The data are taken at 120 GHz, with the same radius of curvature and coupling hole diameter as the resonator in Fig. 2. There is diffraction around both mirrors, with more loss from the smaller mirror. The code accurately predicts the properties of these asymmetric cavities. It is interesting to compare Figs. 2 and 3 to observe the effect of enlarging one of the mirrors. The increase in Q at larger separations indicates the losses are increasing more slowly than the separation.

Another valuable measurement is the effect of misaligned mirrors on the Q. Perrenoud *et al.* [6] found that a 0.5° tilt resulted in a 50% degradation of Q for their configuration. This information is important because the mirror holders must be attached to the superconducting magnet dewar, and it is difficult to estimate how well the mirrors are aligned when the magnet is cooled. Fig. 4 shows the effect of mirror misalignment on Q for one of the asymmetric cavities. The mirror separation is 0.158 m, the frequency is 94 GHz, and the mirrors are 50 and 55 mm in diameter. The Q begins degrading after 1° of misalignment. By 2°, the Q is reduced by 20%. The small scatter of the data for tilts less than 1° is indicative of the reproducibility of the measurement. In general, the sensitivity of the resonator to misalignment depends upon mirror size and separation. Increasing the separation to 0.25 m has little effect on sensitivity to alignment for this cavity.

There are several sources of error in these measurements of Q versus separation. If the frequency sweep is not perfectly linear in time, a systematic error will be present. Secondly, there is a random error in reading the FWHM from the oscilloscope. A third source of error is due to an occasional asymmetry in the shape of the resonance on the oscilloscope. This is caused by an improper position of the pickup horn with respect to the diffracted fields, and can be corrected by adjusting the horn's position. Hence, the measured values should be accurate to better than $\pm 10\%$. This error can be lowered to below $\pm 5\%$ with calibration and careful technique.

V. Conclusions

Extensive measurements have been performed on open resonators with mirror separations approaching confocal. A cold-test apparatus has been assembled to study the properties of a variety of quasi-optical gyrotron resonators at frequencies close to 94 and 120 GHz. Values of Q between 10000 and 100000 have been measured, with corresponding output couplings from 1% to 20%. The data are in good agreement with values calculated from scalar diffraction theory for round-trip losses as small as 1%. This represents the first time that the diffraction theory has been validated over a wide range of resonator parameters at millimeter wavelengths. This setup should prove valuable in examining other properties of open resonators, such as polarization, mode pattern, and cavity coupling.

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