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MEASUREMENT OF THE ELECTRIC FIELD PATTERN OF A FABRY-PEROT RESONATOR USED IN QUASI-OPTICAL GYROTRONS

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The field pattern of the resonator used in a quasi-optical gyrotron operating in the millimetre wave range is measured. Two resonators are studied: one composed of a spherical mirror and an ellipsoidal grating and the other symmetric using two mirrors with annular slots. The measurements indicate that the electric field distribution is gaussian, in spite of the complex geometry of the resonator, and thus provide an experimental basis for the assumption often used to compute the efficiency of quasi-optical gyrotrons.

Key words: gyrotron, millimeter-wave, quasi-optical resonator

INTRODUCTION

In a quasi-optical gyrotron (Q.O.G.) [1], the interaction between the electron beam and the microwave field occurs in a Fabry-Pérot resonator. The efficiency of the gyrotron depends on the field pattern. It is often assumed that the lowest order TEM_{00} mode is excited and therefore the pattern used in the theoretical calculations is taken as a gaussian. However the resonator geometry usually deviates from the ideal one, which consists of two spherical mirrors and for which the modes are well understood. For example, slots are machined in the mirrors to extract energy from the resonator [1]. Due to the geometry required to support the outer part of the mirror, no simple approach is available to compute the field pattern inside the resonator. More recently [2], a novel resonator structure has been proposed to couple the power to a gaussian mode, necessary for efficient propagation. In this configuration, one of the mirrors is replaced by a grating. The grating is designed assuming that the incident field is gaussian. However no theoretical studies have been performed to ensure that this assumption is still valid in the resonator. Since the efficiency of interaction between the electron beam and the microwave field depends on the field distribution, a measure of the field pattern is of importance to understand the behaviour of the gyrotron. In this paper we describe the results from measurements based on the use of the frequency shift induced by a localized dielectric perturbation [3,4,5,6]. The method is applied to the two types of Fabry-Pérot resonators mentioned earlier.

THEORY

The measurement method is based on the perturbation induced by a small dielectric (magnetic) body placed in the resonator. The perturbation of the electric (magnetic) field in the resonator causes a shift of the resonant frequency which is proportional to the square of the electric (magnetic) field [3].

Consider a resonant cavity of volume V. A small perturbation of volume Δ ($\Delta \ll V$) is inserted into V. It has a relative dielectric constant ε and relative susceptibility μ. The calculations outlined in Ref. [3] yield the variation Δf of the resonant frequency f_0 as a function of the electromagnetic quantities $\underline{E}_0$, $\underline{P}$ and $\underline{H}_0$, $\underline{M}$

$$\frac{\Delta f}{f_0} = \frac{\frac{1}{2}\left[\underline{H}_0 \cdot \underline{M} + \underline{E}_0 \cdot \underline{P}\right]}{2W} \qquad (1)$$

E_0 and H_0 are the electric and magnetic fields in the unperturbed resonator, $\underline{P}$ and $\underline{M}$ the electric polarization and the total magnetic moment, and W the electromagnetic energy stored in the resonator. Formula (1) is valid when the dimensions of the perturbation are smaller than the wavelength λ so that the field inside the volume Δ can be considered constant.

In the case of a non-magnetic sphere of radius R (μ=1), Eq. (1) reduces to:

$$\frac{\Delta f}{f_0} = -\frac{1}{4W}\,\frac{\varepsilon-1}{\varepsilon+2}\,\varepsilon_0\, R^3\, |E_0|^2 . \qquad (2)$$

The shift of the frequency is directly proportional to the square of the amplitude of the electric field.

1. Experimental set-up

The experimental set-up is shown in Fig. 1. The microwaves are generated by a carcinotron ($P_{RF} \leq 1$ W, f_{RF}=90 to 120 GHz). Two different types of Fabry-Pérot resonators are investigated: a resonator where a diffraction grating replaces one spherical mirror [2] and a resonator composed of two identical spherical mirrors with annular slots [1]. A detailed description of the resonators will be presented in subsequent sections.

The coupling of the microwave energy to the resonator is made through a hole of 1 mm diameter drilled in the centre of the spherical mirror. A fraction of the circulating power in the resonator is extracted through a second hole slightly off-centre. This output signal is fed into a lock-in system (Fig. 1) to lock the frequency of the carcinotron to a resonant frequency of the resonator. The frequency determination is performed using a spectrum analyzer.

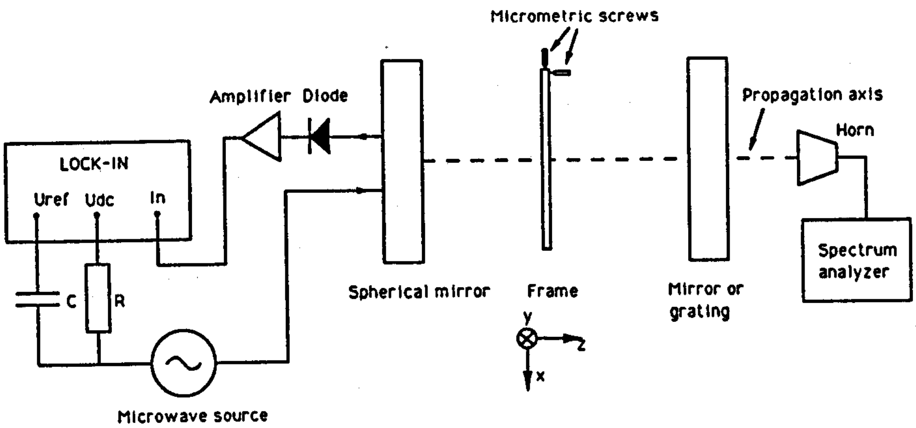

Fig. 1: Experimental set-up. The z-axis is the axis of the resonator.

The perturbing body is positioned in the centre of a frame supported on two nylon wires of 0.14 mm diameter. The frame is fixed on a motor which allows displacement of the dielectric body in the x-y plane. This assembly is mounted on a support which can be moved along the x and z axe using micrometric screws. The field pattern along the three directions x, y and z can thus be measured.

The dielectric perturbing body must satisfy the following two conditions:

- Its dimensions must be smaller than the wavelength. At the operating frequency (f ≈ 100 GHz), a diameter of about 1 to 2 mm is used.

- The dielectric must produce a sufficient frequency shift (>2 - 3 MHz) to be observed with the spectrum analyzer. Several dielectric materials such as PVC, teflon, wood, compressed wood, biological material, stycast, plastics, alumina and macor have been used. The best results were obtained with the biological material and the compressed wood: at the beam waist position, the maximum frequency shift is 4 to 5 MHz. The other materials produce a shift smaller than 3 MHz.

In the experiment, as the dielectric is moved to the region of zero electric field after a long period of operation, the frequency shift does not decrease to zero. To minimize this spurious effect (which may be due to a shift of the resonant frequency caused by variations of temperature), all measurements have been performed in a minimum of time, typically 20-30 minutes.

2. Resonator with an ellipsoidal diffraction grating

The preferred high power transmission lines designed for electron cyclotron wave systems in thermonuclear plasma research are HE_{11} waveguides. In transferring power from a microwave source to an HE_{11} waveguide, a gaussian beam is required to ensure an efficient power coupling. In a Q.O.G., the usual methods of output coupling [7,8], do not provide a gaussian beam. A new scheme has been proposed where one of the mirrors is replaced by a grating arranged in the -1 order Littrow mount. In this arrangement, only two orders of diffraction exist: the -1 order which provides the feedback power to the resonator and the 0 order which provides the output. The grating is designed using the Littrow condition

$$2\,d \sin\theta = \lambda \qquad (3)$$

for a given incident gaussian beam [2]. d is the groove period and θ the incidence angle. An ellipsoidal support is chosen to reduce the depolarization associated with the curvature of the grooves.

The purpose of the experiment is to verify that in this resonator the field pattern is gaussian, as in a conventional Fabry-Pérot resonator, and to localize the position of the beam waist.

The schematic of the resonator is presented in Fig. 2. Its main characteristics are given in Table I.

Operating frequency [GHz]	92.4
Beam waist [mm]	9.31
Mirror separation [mm]	400
Spherical mirror radius of curvature R [mm]	235
Diffraction angle θ [°]	28
Experimental two way loss T [%]	11
Grating support	Ellipsoidal

Table I : Parameters of the resonator with grating.

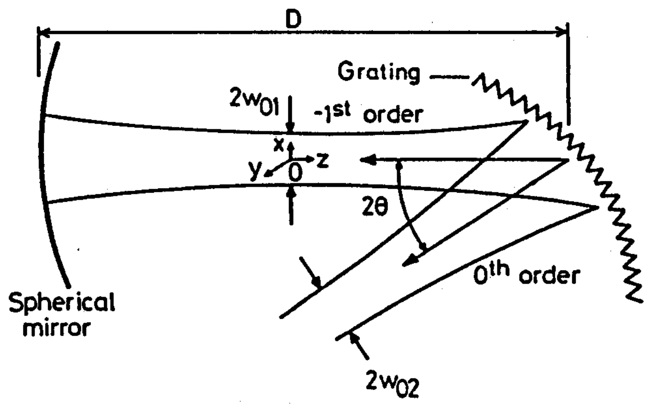

Fig. 2 : Description of the resonator.

An interesting observation using this type of resonator is the behaviour of its quality factor Q for several angles θ of the grating (θ = 27.5°, 28°) as a function of the frequency. The quality factor is obtained by measuring the full-width at half-maximum of the resonance peak. The results are shown in Fig. 3. The frequency dependence of Q changes with the angle θ. A preferential mode, which maximizes Q, exists for each angle of the resonator. It is this mode which best satisfies the Littrow condition [2]. For the other adjacent modes, the Littrow condition is not as well satisfied as for the central mode and, though they are still resonant modes, the resonator behaves as if it were misaligned. The maximum quality factor for the curves are not equal, in agreement with theory. This is an important difference between this type of resonator and conventional resonators for which the quality factor of longitudinal modes are almost constant within the instability bandwidth of the gyrotron instability.

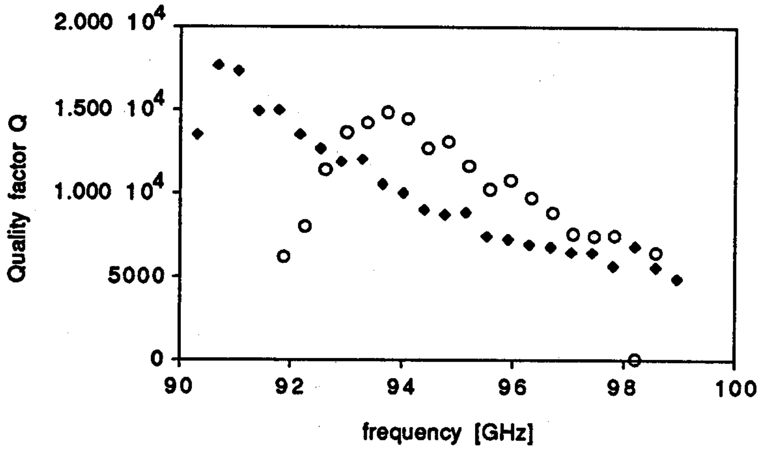

Fig. 3 : Quality factor of the resonator as a function of resonant frequency (◦ = 27.5°, ♦= 28°).

The experimental results of the electric field distribution measured in the x-y plane are shown in Fig. 4. The line is the best gaussian fit through the points (fit parameter > 99.8%).

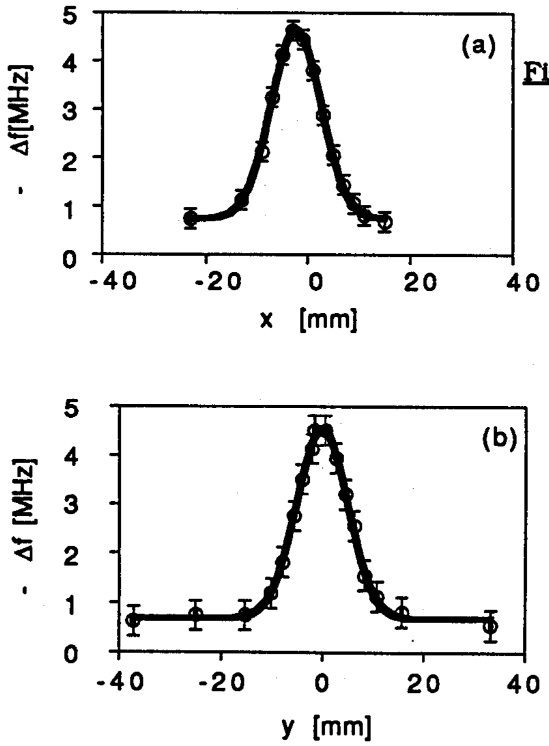

Fig. 4 : Mirror-grating resonator: measured frequency shift at beam waist for 93.32 GHz.
(a) distribution along x axis
(b) distribution along y axis ($w_{0x}=w_{0y}$ = 9.4 ± 0.2 mm).
Biological material is used as the perturbing dielectric .

The beam waist w_0 (defined as the full width at half-maximum) is equal in both x and y directions: $w_{0x} = w_{0y} = 9.4 \pm 0.2$ mm. They are in excellent agreement with the design value of 9.315 mm. There is no distortion of the pattern since the beam waist in the two directions are equal.

We also measure the periodicity of the electric field intensity along the optical axis z by varying the location of the dielectric along the z axis while keeping x and y fixed. The result is shown in Fig. 5. The distance between two consecutive maxima is 1.58 mm ± 0.06 mm and corresponds to one half-wavelength at the operating frequency.

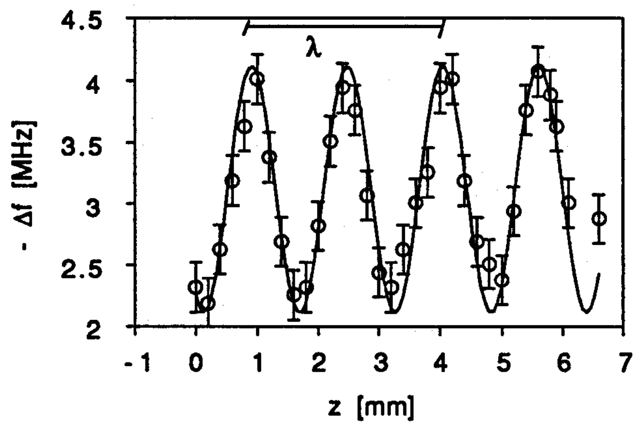

Fig. 5 : Periodicity of the field at f_0 = 95 GHz along the optical axis.

3. Resonator composed of two identical mirrors with annular slots

In the first Q.O.G. experiments, slotted resonators were used [1]. The slots in the mirrors were machined to couple the energy from the resonator to an overmoded waveguide. A schematic of the mirror is presented in Fig. 6. The inner radius R_1 determines the total diffractive loss while R_2 and R_3 are designed to optimize the fraction of the diffracted power which passes through the slots. The width D of the spoke is determined by the technological constraint imposed by the cooling of the central part of the mirror.

The characteristics of the mirrors and the resonator are given in Table II. The experimental set-up is the same as Sec. 2 except that the coupling hole is a rectangular hole drilled in the centre of one mirror. The hole is fed by a standard WR-10 rectangular waveguide. With this arrangement, a well-defined polarization is imposed inside the resonator.

Mirror outer radius R_3 [mm]	70
Slot outer radius R_2 [mm]	43.2
Slot inner radius R_1 [mm]	26
Spoke width D [mm]	8.4
Operating frequency [GHz]	92.8
Beam waist [mm]	12.2
Mirror separation [mm]	310
Radius of curvature R [mm]	288
Experimental two way loss [%]	≈10
Resonator g factor	- 0.076

Table II. Parameters of the resonator using slotted mirrors.

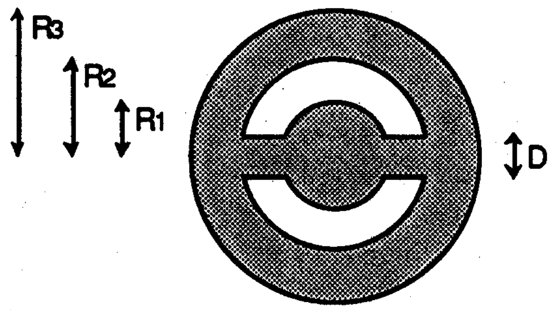

Fig. 6 : Schematic of the slotted mirrors. The rectangular waveguide coupling hole as shown generates a field with a polarization, which is defined as vertical. For the horizontal polarization the waveguide is rotated by $\pi/2$.

The field distribution for vertical and horizontal polarizations are measured by rotating the rectangular coupling hole by $\pi/2$. The results are shown in Figs. 7 and 8. The electric field intensity pattern, measured for both polarizations, does not depend on the polarization despite the relatively large asymmetry introduced by the spoke width D (= 8.4 mm). The pattern is gaussian and is seen to have azimuthal symmetry as the beam waists are roughly equal in the three directions where measurements are performed: along Ox (w_{0x} =9.8 mm), Oy (w_{0y} =10.3 mm), and at 45° (w_{0xy} = 10.5 mm).

Again in Figs. 7 and 8, the shift of the reference frequency between the first and the last measurements can be noticed: the zero level, corresponding to the region of zero electric field ($|x| > 20$ mm or $|y| >$ 20 mm) is different at the beginning and at the end of the scan. This effect, as mentioned previously, is due to the drift of the resonant frequency with time.

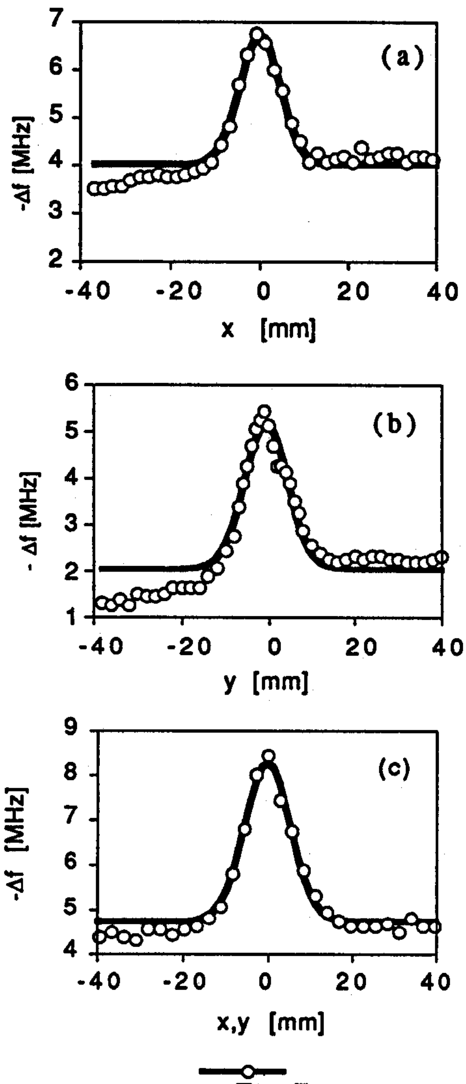

Fig. 7

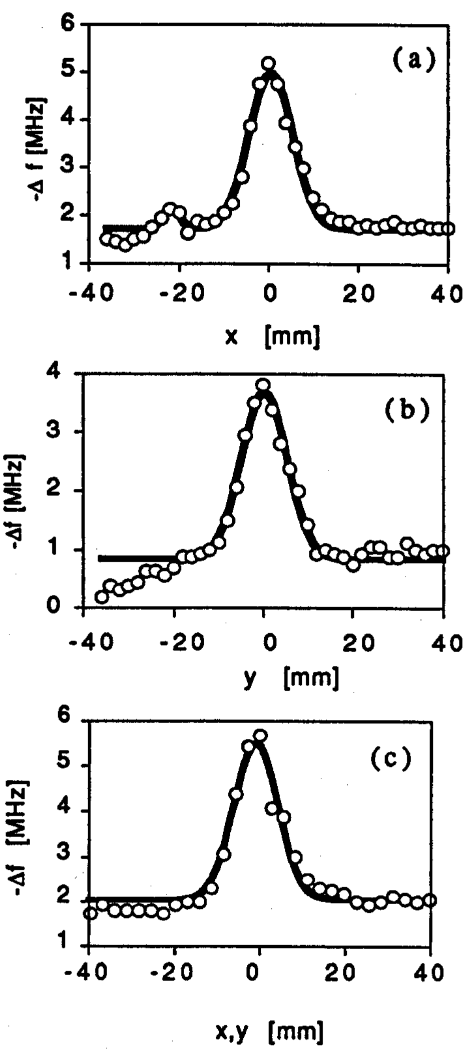

Fig. 8

Figs. 7 and 8 : Electric field intensity distribution in the horizontal polarization (Fig. 7) and in the vertical polarization (Fig. 8) measured at the beam waist. ((a) pattern along x, (b) pattern along y, (c) pattern along the diagonal).

Great care must also be exercised in aligning the resonator. For example, we observe in some cases that the field distribution is distorted. In Fig. 9, besides the principal maximum, there is a secondary maximum at x = 20 mm. This can be due to an asymmetry in the resonator geometry or a misalignment of the mirrors.

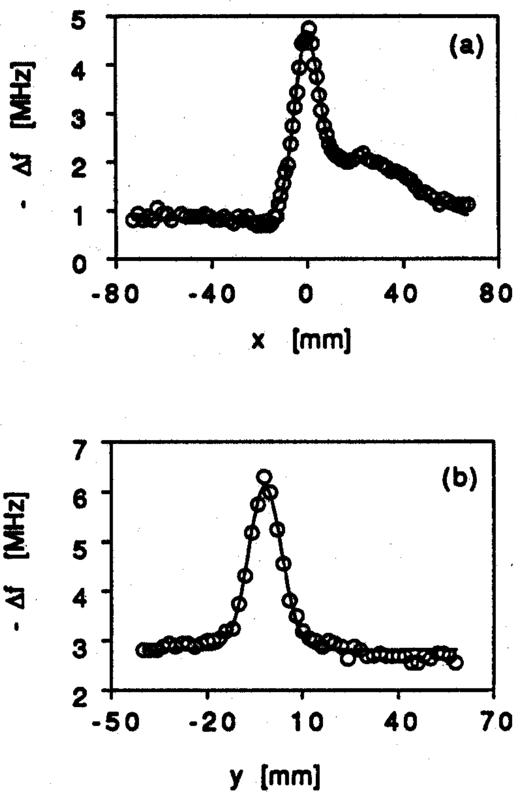

Fig. 9: Electric field intensity distribu-tion of the resona-tor formed of two mirrors with annular slots. The measurement is performed at the beam waist, (a) pattern along Ox measured at x = 0 mm, (b) pattern along Oy measured at y = 0 mm.

CONCLUSIONS

The distribution of the electric field intensity at millimetre wavelengths is determined using the perturbation method. For both types of resonators (one using a grating and one with slotted mirrors), we have confirmed that the pattern is gaussian, despite the non-ideal geometry of the resonator. The experimental result is especially important in the case of the resonator with a grating since the grating cannot be theoretically considered as a simple partially transmitting mirror as both distortion and cross-polarization have been observed in the output beam [2]. Moreover, the design of the grating, as discussed in [2], does not consider the influence of multiple reflections between the spherical mirror and the grating, and hence the final pattern in the resonator must be determined experimentally. These experimental results also support the assumption made in the theory of Q.O.G. that the field pattern is gaussian.

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