Design of a quasi-optical system with variable output beam size

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I. OGAWA†¶, T. IDEHARA‡, S. MAEKAWA† and W. KASPAREK§

A quasi-optical system consisting of a quasi-optical antenna and two ellipsoidal mirrors can convert the gyrotron output (TE_{15} mode, 354 GHz) into a gaussian-like beam. The waist size of the beam produced is adjusted by moving a second ellipsoidal mirror. The second mirror with focal length of 520 mm offers a tunable range from 2.0 mm to 5.4 mm, and those with focal lengths of 1190 mm and 2390 mm offer other tunable ranges from 5.1 mm to 12.9 mm and from 12.0 mm to 25.1 mm, respectively.

1. Introduction

Up to now, molecular vapour lasers (Semet *et al.* 1980, Kawahata *et al.* 1988) and backward-wave oscillators (Morino *et al.* 1997) have been the principal power sources in the submillimetre wavelength range. However, some applications, such as plasma scattering measurements (for example, Terumichi *et al.* 1984, Fekete *et al.* 1994, Suvorov *et al.* 1997) need more intense waves. High frequency gyrotrons are the most promising candidates to deliver intense waves of several hundred watts up to several kilowatts (Zaytsev *et al.* 1974, Spira-Hakkarainen *et al.* 1990, Idehara *et al.* 1995).

Before these gyrotrons can be used as power sources, it is necessary to convert the output into a gaussian beam. Unlike molecular vapour lasers, gyrotrons produce hollow cone-shaped beams, which are far from what is usually required. For most purposes the conversion system into a gaussian beam, which offers the beam size tunability, is required.

In an earlier paper (Ogawa *et al.* 2000), we presented a beam size tunable system consisting of a quasi-optical antenna (Vlasov and Orlova 1974) and two parabolic cylinder mirrors. However, the system needs somewhat complicated operations, namely, movements and rotations of both mirrors.

In the work presented here, the target gaussian beam is obtained by using a quasi-optical antenna and two focusing mirrors (Ogawa *et al.* 1999a), and the beam size tunability is realized only by moving the second focusing mirror. While we can design the system using gaussian optics, it is, however, necessary to carry out a full calculation of the radiation patterns in order to see that the discrepancies are not too large.

The main purpose of this paper is to investigate the effectiveness of this system.

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2. Calculation of radiation patterns

If the electromagnetic fields produced by a quasi-optical antenna are known, then those at any subsequent point can be obtained by solving the Helmholtz equation together with the boundary conditions on each mirror. Solving the Helmholtz equation is equivalent to calculating the Huygens equation (e.g. Kong 1986).

The first component in the system (figure 1) is the quasi-optical antenna (figure 2) consisting of a circular waveguide (internal radius $a_w = 14$ mm) with a step-cut and a parabolic cylinder reflector (focal length $f_p = 21.75$ mm). The antenna converts the output (TE_{15} mode, 354 GHz) of Gyrotron FU II (Idehara *et al.* 1992) into a linearly-polarized beam. Its electric and magnetic fields are parallel to the x- and y-directions, respectively.

Radiation reflected from the parabolic cylinder reflector of the quasi-optical antenna is treated as if it came from a plane image source lying behind the parabolic cylinder with emission angle $\alpha(= 8.233°)$ (Wada and Nakajima 1986, Brand *et al.* 1990). The fields over this image source are calculated using geometrical optics.

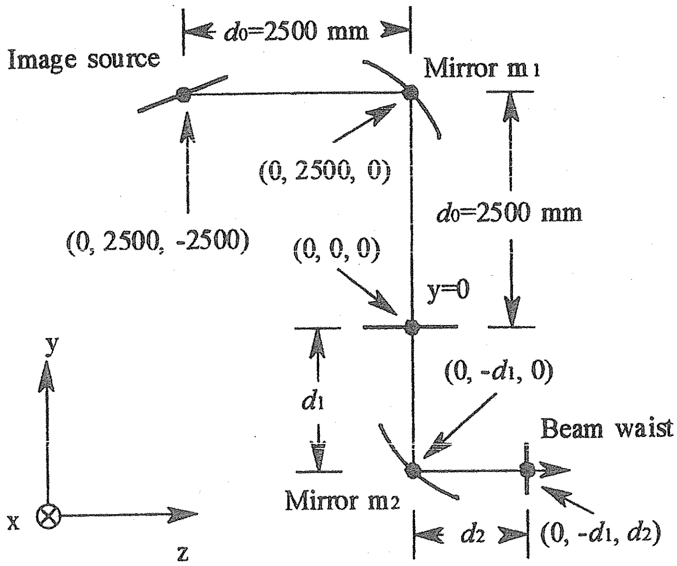

Figure 1. Quasi-optical system. Plane image source used in the calculation of the subsequent radiation patterns of the quasi-optical antenna. The beam produced by the image source propagates along the z-axis.

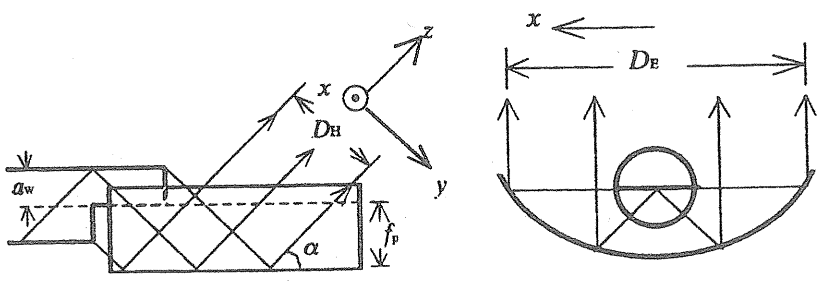

Figure 2. Quasi-optical antenna.

The incident electromagnetic fields at the first mirror are calculated using the Huygens equation. The electromagnetic fields reflected from the mirror are given by the boundary conditions (Ogawa *et al.* 1999a).

The electromagnetic fields on subsequent mirrors are obtained by repeated use of the Huygens equation and the boundary conditions together with the previously calculated results as the source fields.

3. Treatment of a beam using gaussian optics

To design the system (figure 1), the image source is located so that the beam with polarization in the x-direction propagates along the z-direction.

The image source produces the far-field consisting of a main beam with circular cross-section and additional sidelobes. The spot size of the main beam is accurately given by assuming a gaussian beam whose waist (waist size $w_0 = 25.4\,\mathrm{mm}$) is located at the centre of the image source (Ogawa *et al.* 1999b). Because the main beam is similar to a gaussian beam, such a treatment is justified. The intensity of the gaussian beam is given by

$$I = \frac{2P_0}{\pi w^2} \exp\left(-2\frac{x^2 + y^2}{w^2}\right) \tag{1}$$

where w is the spot size and P_0 is the total beam power. We will define the spot size of such a beam as the radius of the $-8.69\,\mathrm{dB}$ ($= e^{-2}$) contour.

Beam propagation and focusing are most conveniently treated by the use of the complex beam parameter q (e.g. Siegman 1971). It is defined by

$$\frac{1}{q} = \frac{1}{R_w} - j\frac{\lambda}{\pi w^2} \tag{2}$$

where R_w is the curvature radius of the wave front.

At the beam waist, $R_w \to \infty$. Therefore, the complex beam parameter q_0 is

$$q_0 = j\frac{\pi w_0^2}{\lambda} \tag{3}$$

When a beam propagates along some distance or is focused by any component, the complex beam parameter changes. After propagating a distance d, the complex beam parameter q changes to a new value q' given by

$$q' = q + d \tag{4}$$

After a focusing component, it changes from q to a new value q' given by

$$\frac{1}{q'} = \frac{1}{q} - \frac{1}{f} \tag{5}$$

where f is the focal length of the focusing component.

4. Design of the system using gaussian optics

In the system (figure 1), the focal length f_1 of the mirror m_1 coincides with the distance $d_0 (= 2500\,\mathrm{mm})$, namely, $f_1 = d_0$. For this special arrangement, the far-field of the image source appears in the $y = 0$ plane (Ogawa *et al.* 1999a).

If we treat the main beam as the gaussian beam having a waist (waist size $w_0 = 25.4\,\text{mm}$) at the position of the image source, as can be seen from equations (4) and (5), the complex beam parameter q_0' at the $y = 0$ plane is given by

$$q_0' = -\frac{f_1^2}{q_0} \tag{6}$$

where q_0 is the complex beam parameter at the image source. Equations (3) and (6) give the beam waist w_0' at the $y = 0$ plane as

$$w_0' = \frac{f_1\lambda}{\pi w_0} \tag{7}$$

The equations show that since one waist is at the image source, the beam will come to a waist at the $y = 0$ plane.

The size of the mirror m_1 is chosen so that the mirror projects a rectangular plane of 120 mm in the x-direction and 185 mm in the y-direction in consideration of the beam intensity profile at the mirror m_1 (figure 3 (*a*)). The shape is defined by an ellipse with focal points $(0, 2500, -10\,000)$ and $(0, -833, 0)$ resulting in a focal length of $f_1 = 2500\,\text{mm}$.

The intensity profile at the $y = 0$ plane is shown in figure 3 (*b*). The beam consists of a main beam with circular cross-section and additional sidelobes. The spot sizes w_x' (=26.2 mm) and w_z' (=26.9 mm) of the main beam agree well with the waist size w_0' (=26.6 mm) given by equation (7). This waist size w_0' will be the starting point in our design. According to gaussian optics, the final waist size w_0'' of the beam produced is varied by vertically moving the mirror m_2 or changing the focal length f_2 of the mirror m_2. First we will determine the distance d_1 using $f_2 = 520\,\text{mm}$, to realize a waist size tunability from $w_0'' = 2.0\,\text{mm}$ to $w_0'' = 5.0\,\text{mm}$. This value f_2 is selected in consideration of a practical distance d_1 (<7000 mm).

The design is accomplished by converting the complex beam parameter q_0' into the complex beam parameter q_0'' at the beam waist according to equations (4) with $d = d_1$ and (5) with $f = f_2$. The value of q_0'' is also obtained using equation (3) with $w_0 = w_0''$. If we notice that q_0'' is purely imaginary, the distance d_2 is given by

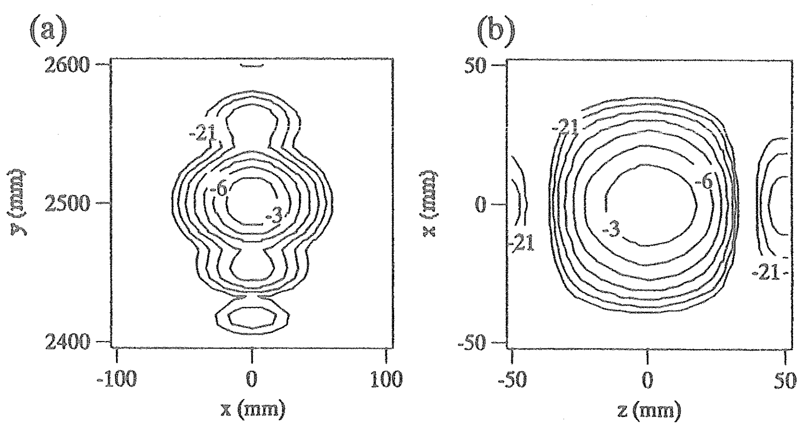

Figure 3. Calculated intensity contours (*a*) at the mirror m_1, (*b*) at the $y = 0$ plane. Contours are in decibels relative to the intensity maximum.

$$d_2 = -\mathrm{Im}(q') \tag{8}$$

where q' is the complex beam parameter just after reflection by mirror m_2.

The same procedure using gaussian optics has been applied to two other cases covering different beam size ranges from $w_0'' = 5.0\,\mathrm{mm}$ to $12.0\,\mathrm{mm}$ and from $w_0'' = 12.0\,\mathrm{mm}$ to $24.0\,\mathrm{mm}$. The results are listed in table 1.

		Beam waist	
f_2 (mm)	d_1 (mm)	d_2 (mm)	w_0'' (mm)
520	6909	556.3	2.0
	1412	551.6	5.0
1190	6943	1394	5.0
	1512	1256	12.0
2390	6987	3329	12.0
	2792	2719	24.0

Table 1. Output beam waist as a function of geometry and focal length of mirror m_2, obtained by gaussian optics.

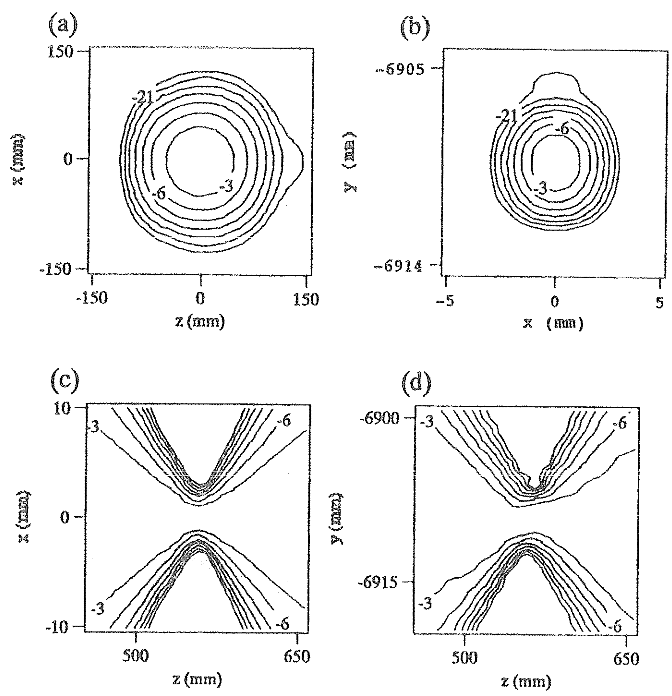

Figure 4. Calculated intensity contours for the target waist size of $w_0'' = 2\,\mathrm{mm}$ using the mirror m_2 with the focal length $f_2 = 520\,\mathrm{mm}$. (*a*) At the mirror m_2, (*b*) at the beam waist. Contours are in decibels relative to the intensity maximum. (*c*) and (*d*) In the vicinity of the beam waist. Contours are relative to the intensity along the z-axis.

5. Calculation results using the Huygens equation

In order to improve the quality of the beam produced, it is necessary to remove the sidelobes from the far-field of the image source (figure 3 (*b*)). This is experimentally done by inserting a filter to block the sidelobes in the $y = 0$ plane.

At first, the incident electromagnetic fields at the $y = 0$ plane are calculated. In order to remove the sidelobes, the sizes of the filtering diaphragm are selected to 80 mm in the x-direction and 75 mm in the z-direction, and its centre is located at the point $(0, 0, -2.5)$. The electromagnetic fields on the subsequent mirror m_2 are obtained by repeatedly using the Huygens equation with the previous calculated results as the sources.

Calculated intensity contours for $d_1 = 6909$ mm and $d_1 = 1412$ mm are shown in figures 4 and 5, respectively. The shape of the mirror m_2 is defined by an ellipse with focal points $(0, 10\,000 - d_1, 0)$ and $(0, -d_1, 548.5)$ (see figure 1) so that it has a focal length of $f_2 = 520$ mm. The spot sizes w_x'' and w_y'' and the distances d_{x2} and d_{y2} between the centre of the mirror m_2 and the beam waist are listed in table 2 for comparison. These values are in good agreement with those for the cases of $w_0'' = 2$ mm and $w_0'' = 5$ mm obtained by gaussian optics (table 1). Therefore, this mirror offers a tunability from 2.0 mm to 5.4 mm.

In this system, different tunable ranges from 5.1 mm to 12.9 mm (figures 6 and 7) and from 12.0 mm to 25.1 mm (figures 8 and 9) are attained by replacing the mirror m_2 by focusing a mirror with focal lengths of $f_2 = 1190$ mm and $f_2 = 2390$ mm, respectively. The mirror shapes are defined by ellipsoids with focal points

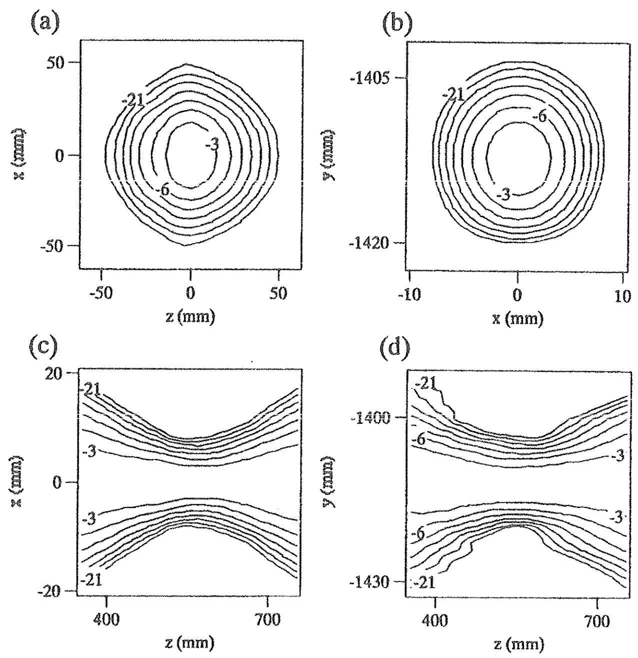

Figure 5. Calculated intensity contours for the target waist size of $w_0'' = 5$ mm using the mirror m_2 with the focal length $f_2 = 520$ mm. (*a*) At the mirror m_2, (*b*) at the beam waist. Contours are in decibels relative to the intensity maximum. (*c*) and (*d*) In the vicinity of the beam waist. Contours are relative to the intensity along the z-axis.

	Beam waist			
f_2 (mm)	d_{x2} (mm)	d_{y2} (mm)	w''_x (mm)	w''_y (mm)
520	556.5	556.7	1.9	2.1
	589.7	550.0	5.2	5.5
1190	1388	1411	4.8	5.3
	1328	1228	12.7	13.1
2390	3319	3319	11.4	12.6
	2906	2655	25.2	24.0

Table 2. The results obtained by numerical calculations of the Huygens equations. The values d_{x2}, d_{y2}, w''_x and w''_y show the distances from the centre of the mirror m_2 to the beam waist in the x- and y-directions and spot sizes of the beam in the x- and y-directions, respectively.

$(0, 10\,000 - d_1, 0)$ and $(0, -d_1, 1350)$, alternatively with focal points $(0, 10\,000 - d_1, 0)$ and $(0, -d, 3141)$.

Because each tunable range overlaps with another, application of three mirrors offers a waist size tunability from 2.0 mm to 25.1 mm.

Concerning characteristics, this system can produce a beam with circular cross-section compared with the system consisting of two parabolic cylinder mirrors with a

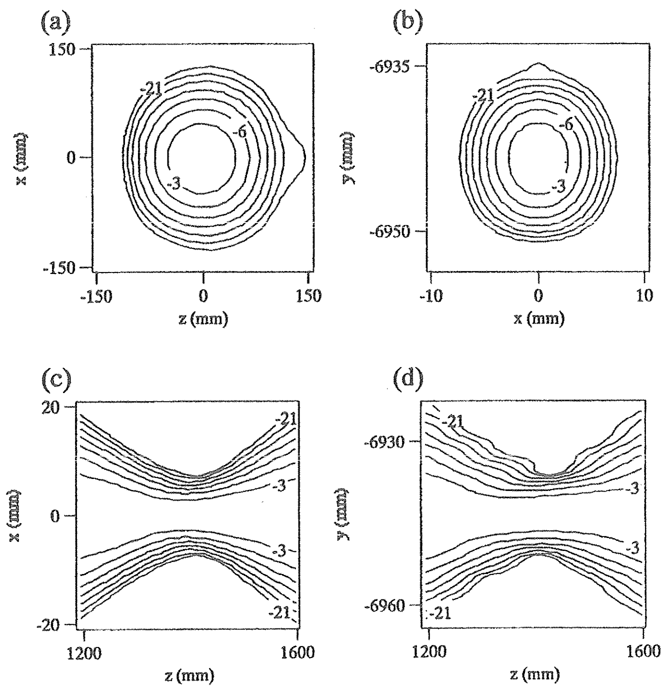

Figure 6. Calculated intensity contours for the target waist size of $w''_0 = 5$ mm using the mirror m_2 with the focal length $f_2 = 1190$ mm. (*a*) At the mirror m_2, (*b*) at the beam waist. Contours are in decibels relative to the intensity maximum. (*c*) and (*d*) In the vicinity of the beam waist. Contours are relative to the intensity along the z-axis.

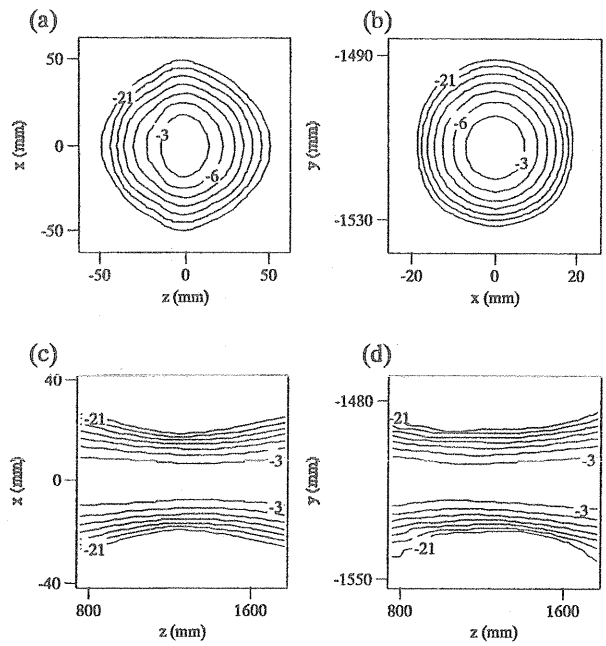

Figure 7. Calculated intensity contours for the target waist size of $w_0'' = 12\,\mathrm{mm}$ using the mirror m_2 with the focal length $f_2 = 1190\,\mathrm{mm}$. (*a*) At the mirror m_2, (*b*) at the beam waist. Contours are in decibels relative to the intensity maximum. (*c*) and (*d*) In the vicinity of the beam waist. Contours are relative to the intensity along the *z*-axis.

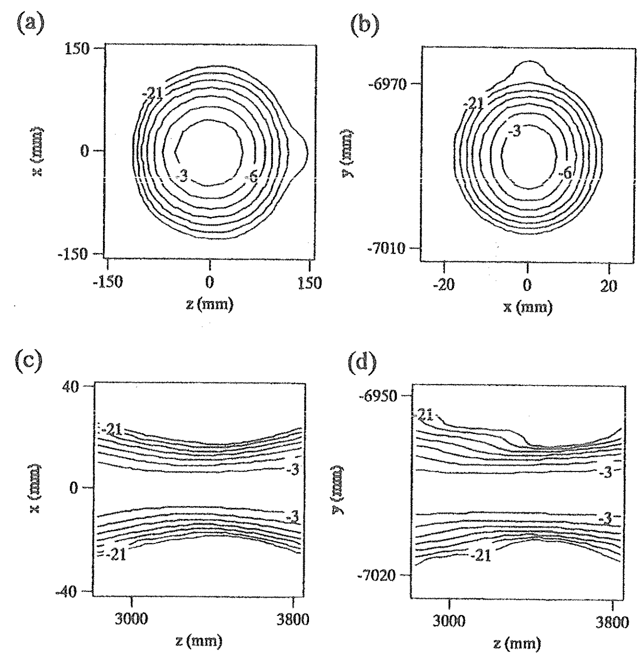

Figure 8. Calculated intensity contours for the target waist size of $w_0'' = 12\,\mathrm{mm}$ using the mirror m_2 with the focal length $f_2 = 2390\,\mathrm{mm}$. (*a*) At the mirror m_2, (*b*) at the beam waist. Contours are in decibels relative to the intensity maximum. (*c*) and (*d*) In the vicinity of the beam waist. Contours are relative to the intensity along the *z*-axis.

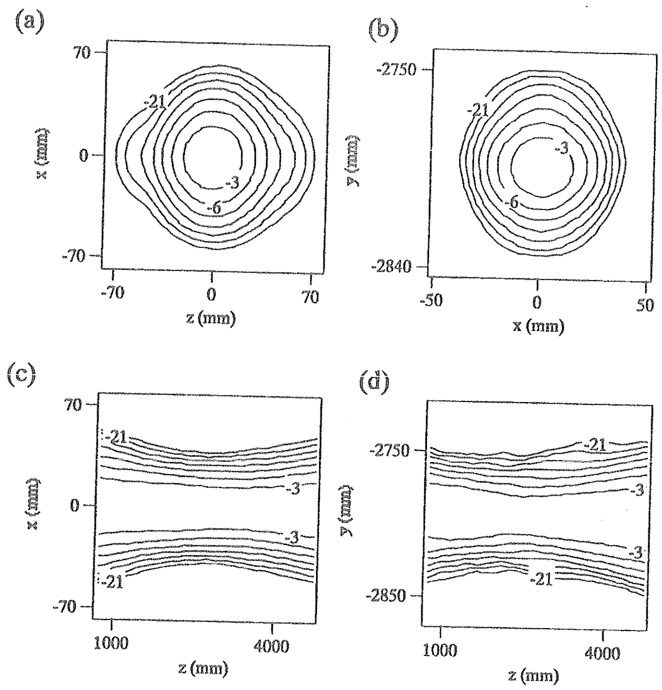

Figure 9. Calculated intensity contours for the target waist size of $w_0'' = 24$ mm using the mirror m_2 with the focal length $f_2 = 2390$ mm. (*a*) At the mirror m_2, (*b*) at the beam waist. Contours are in decibels relative to the intensity maximum. (*c*) and (*d*) In the vicinity of the beam waist. Contours are relative to the intensity along the *z*-axis.

quasi-optical antenna (Ogawa *et al.* 2000). In addition, most of power from the image source (88%) still arrives at the beam waist in spite of the truncation of the sidelobes at the $y = 0$ plane.

6. Conclusion

A system consisting of a quasi-optical antenna and two focusing mirrors can convert the TE_{15} mode output (354 GHz) of the Gyrotron FU II into a gaussian-like beam. The combination of the antenna and the first mirror produces the far-field of the antenna.

The beam quality is improved and the design is significantly simplified by truncating the sidelobes of the far-field. In spite of the beam truncation, most of the power (88%) of the image source is transferred to the waist. This enables us to produce an intense gaussian beam in the submillimetre wavelength range.

This system offers a waist size tunability from 2.0 mm to 5.4 mm only by moving the second mirror. Different tuning ranges are available by replacing the mirror. The application of three mirrors offers the waist size tunability from 2.0 mm to 25.1 mm.

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