Quasi-Optical Techniques

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Invited Paper

Quasi optics involves beams of radiation propagating in free space which are limited in lateral extent when measured in terms of wavelengths and for which diffraction is of major importance. Employing beams which are moderately well collimated and which have a Gaussian distribution of field and power transverse to their axis of propagation allows the simple and elegant theory of Gaussian optics to be applied. Gaussian beams and Gaussian optics systems have come to play a major role at millimeter wavelengths and to dominate submillimeter system design. This is a result of the very low loss over extremely broad bandwidths that can be obtained with this means of propagation, together with the wide variety of components that can be effectively realized.

In this review I first summarize the basic theory of quasi-optical Gaussian beam propagation and beam transformation by simple optical elements, and then briefly discuss coupling to and between Gaussian beams. Guidelines for Gaussian optics system design are reviewed, the most important being beam truncation and matching. I discuss passive components in the terahertz frequency range based on quasi-optical propagation, including polarization processors, filters, diplexers, and ferrite devices, and describe some active quasi-optical devices, including multielement oscillators, frequency multipliers, and phase shifters. Some specific applications of quasi-optical systems are also briefly described.

I. Introduction

The development of an efficient method of controlled propagation of radiation is a prerequisite for exploitation of any part of the electromagnetic spectrum. For example, coaxial transmission lines allow systems to be constructed at radio to microwave frequencies, while development of very low loss fibers has provided a major impetus for the development of optical communications systems in recent years. There may be a multiplicity of transmission media, as is the case at centimeter wavelengths today, with coaxial lines, microstrip, and waveguide all playing different valuable roles.

With a dramatic increase in activity at terahertz frequencies during the past few years in such diverse fields as radio astronomy, remote sensing of the atmosphere, and plasma diagnostics, the issue of the appropriate transmission medium at short millimeter and submillimeter wavelengths has taken on added importance. Guided-wave techniques developed for lower frequencies become prohibitively lossy at submillimeter wavelengths. For example, if we consider fundamental-mode rectangular waveguide made of material with a given conductivity, the loss increases as (frequency)$^{1.5}$ [1]. In practice, effective surface resistivities in the submillimeter region are several times higher than expected from dc parameters, and a realistic attenuation for fundamental-mode metallic waveguide at 900 GHz is $\cong$ 0.3 dB/cm. The absorption of dielectric materials also is relatively large in this frequency range. A low-loss material such as polyethylene has an absorption coefficient of 0.65 dB/cm at 500 GHz [2]. There is thus a strong impulse to find a lower loss method of transmission to achieve high-performance systems at submillimeter wavelengths.

Quasi-optical propagation is one solution to this problem. It is based on the idea of a fairly well collimated beam of radiation propagating in free space. For practical reasons, particularly at longer wavelengths, we wish to restrict the maximum beam size to a reasonable number of wavelengths. Consequently, diffraction is a significant issue for analyzing the basic propagation of a beam of radiation, for designing lenses and mirrors to limit beam growth, and for understanding the behavior of different types of quasi-optical devices. Diffraction theory is in general too complex to be used as a design tool for systems which include numerous interactions of the beam at interfaces, multiple focusing elements, and possibly repeated truncations caused by limited clearances. Fortunately, a relatively simple and elegant theory is available for a beam having a Gaussian amplitude distribution transverse to its axis of propagation, and whose minimum diameter is not too small. The theory of Gaussian beam propagation and Gaussian optics is almost universally used for the analysis of quasi-optical propagation, and allows quite accurate, rapid system design to be carried out. Some of the reviews of quasi-optical propagation that have been published are given in [3], and special emphasis is placed on Gaussian beam analysis in [4].

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II. Gaussian Beam Propagation

A. Historical Overview

Quasi-optical propagation is hardly new—in fact, many of H. Hertz's and J. C. Bose's experiments at the end of the last century on propagation, polarization, refraction, and reflection of electromagnetic waves were carried out using apparatus only a few times larger than the wavelengths employed [5]. The subsequent evolution of radio wavelength technology was primarily oriented toward guided wave propagation. Antenna theory was developed as well, but there was relatively little concern with free-space transmission over short distances, such as those *within* a system.

The modern era of quasi optics had its start in two quite distinct areas of research in the late 1950's and bore fruit in the early part of the following decade. The first was the study of modes in resonators operating at optical wavelengths, which were of great interest in consequence of their application to lasers [6]. The transverse field distributions of the low-loss modes of resonators consisting of a pair of reflecting mirrors were found to be Gaussian functions (multiplied by various polynomials in the case of higher order modes). Analysis of the variation of the electric field distribution as a function of position within the resonator yielded an understanding of Gaussian beam propagation. Much of the early work in this field is summarized in the excellent review article by Kogelnik and Li [7].

The second line of investigation leading to the development of Gaussian beam theory was the study of beam waveguides, which are repeated sequences of lenses or mirrors designed to achieve low-loss propagation of a beam of radiation over large distances. Analyses using diffraction theory revealed that the low-loss electric field distribution in the beam waveguide is again essentially a Gaussian [8]. Some of the early work on beam waveguides was oriented toward millimeter-wave communications [9], and while these have not yet seen widespread use, understanding of quasi-optical propagation has benefited significantly from these efforts.

B. Gaussian Modes

The development of Gaussian modes can be obtained from various starting points, including diffraction from apertures and resonator reflectors, and solution of the paraxial wave equation [10]. In the context of the last approach, the scalar field satisfies the Helmholtz equation

$$\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2 + \partial^2 u/\partial z^2 + k^2 u = 0, \qquad (1)$$

where $k = 2\pi/\lambda$ and we have assumed an overall time dependence $\exp(i\omega t)$. For a beam propagating in the positive z direction, we can write

$$u = \exp(-ikz) \cdot \Psi(x, y, z). \qquad (2)$$

If we assume that the beam is moderately well collimated, substitution of (2) with the approximation

$$|\partial^2 \Psi/\partial z^2| \ll 2k \cdot |\partial \Psi/\partial z| \qquad (3)$$

yields the reduced or parabolic wave equation

$$\partial^2 \Psi/\partial x^2 + \partial^2 \Psi/\partial y^2 - 2ik \cdot \partial \Psi/\partial z = 0. \qquad (4)$$

The solutions to this equation are Gauss-Hermite polynomials in rectangular coordinates and Gauss-Laguerre polynomials in cylindrical coordinates [7]. While the higher modes are essential for analysis of general field distributions, and are of interest themselves in certain situations, they are generally undesirable in terms of efficient operation of Gaussian beam systems. We will thus consider here only the fundamental Gaussian mode, which is axially symmetric so that the sole transverse coordinate is r, the distance from the axis of propagation, and $\Psi(r, z)$ has a Gaussian dependence on r.

C. Gaussian Beam Propagation

Defining the plane $z = 0$ to be the location where the beam has its minimum size, or beam waist, we have the fundamental Gaussian distribution

$$\Psi(r, 0) = \exp(-r^2/w_o^2). \qquad (5)$$

Here w_o is the minimum value of the $1/e$ field radius, which occurs at the beam waist, and is called the beam waist radius. At the beam waist, the equiphase surface or phase front of the beam is planar; away from the beam waist, the beam expands but retains its Gaussian form (see Fig. 1(a)). The field distribution at an arbitrary distance from the beam waist is described by the beam radius w (the distance from the axis of propagation for the field to fall to $1/e$ of its on-axis value) and the radius of curvature R (of the spherical wave fronts which describe the equiphase surfaces of the solutions to the paraxial wave equation). Normalizing the field amplitude so that the power flow defined by $P = \int |u|^2 \cdot 2\pi r dr$ is unity, we obtain

$$u = [2/\pi w^2]^{0.5} \exp(-r^2/w^2 - ikz - i\pi r^2/\lambda R + i\phi). \qquad (6)$$

As indicated in Fig. 1(b), the preexponential term in (6) results in the peak field amplitude dropping as beam radius grows. The variation of beam parameters with distance from the beam waist is given by

$$\begin{aligned} w &= w_o \cdot [1 + (\lambda z/\pi w_o^2)^2]^{0.5} \\ R &= z + (\pi w_o^2/\lambda)^2/z \\ \phi &= \arctan(\lambda z/\pi w_o^2). \end{aligned} \qquad (7)$$

In (6), the first term in the exponential is the Gaussian amplitude distribution and the second is the phase of a plane wave propagating along the z axis. The third term gives the phase difference between a plane perpendicular to the axis of propagation and the spherical wave front of radius of curvature R, while the last term is an additional phase shift which changes appreciably only near the beam waist. Defining the confocal or Rayleigh distance by

$$z_c = \pi w_o^2/\lambda, \qquad (8)$$

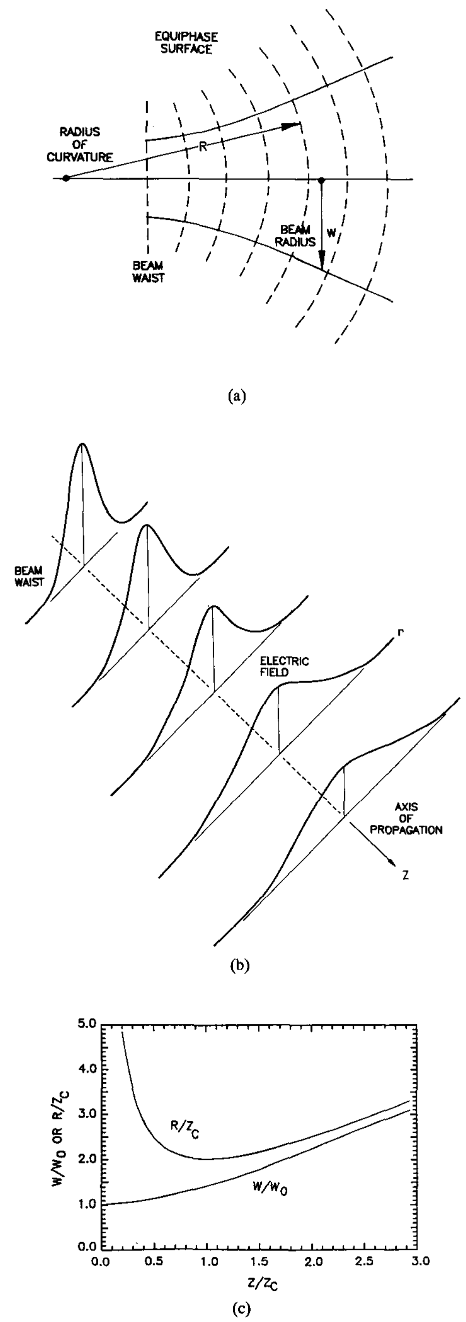

Fig. 1. (a) Schematic view of propagating Gaussian beam showing equiphase surfaces and variation of beam radius away from beam waist. (b) Propagation of fundamental-mode Gaussian beam away from beam waist showing drop in the on-axis electric field strength as beam expands. (c) Variation in radius of curvature and beam radius in normalized units as a function of distance from the waist expressed in units of confocal distance z_c.

we can rewrite (7) in more compact form:

$$\begin{aligned} w &= w_o \cdot [1 + (z/z_c)^2]^{0.5} \\ R &= z + z_c^2/z, \\ \phi &= \arctan(z/z_c). \end{aligned} \tag{9}$$

These remarkably simple equations, which describe the propagation of the fundamental-mode Gaussian beam, are shown schematically in Fig. 1(c). The variation of the beam radius as a function of distance from the beam waist has the form of a hyperbola, with asymptotic growth angle

$$\theta_0 = \lambda/\pi w_o. \tag{10}$$

The radius of curvature drops from its infinite value at the waist to a minimum value $R = 2z_c$ at distance z_c from the waist, and then increases, growing as $R \cong z$ for $z \gg z_c$. The phase ϕ changes by 90° within distance $-z_c$ to $+z_c$ about the beam waist. This phase shift, which is an example of the Guoy shift for focused optical beams [11], is of critical importance in the design of quasi-optical resonators, but is not of much importance for propagating Gaussian beams.

A subject which for many years has received considerable attention is the minimum value of w_o for which the Gaussian solution and the paraxial approximation are valid. In the Gaussian beam solution to the paraxial equation the electric and magnetic fields are perpendicular and are transverse to the direction of propagation. For less well collimated beams, there are corrections to the Gaussian field distribution, which include both a longitudinal component and modifications of the transverse distribution. These modifications, which are developed in several treatments [12], are important for analyzing radiation from antenna systems having highly divergent beams. A reasonably conservative criterion is that we can safely use the paraxial solution for $w_o \geq 0.9\lambda$; in the range $0.45\lambda \leq w_o \leq 0.9\lambda$, the first-order corrections are effective, while for even more divergent beams the Gaussian beam model fails completely [13].

D. Complex Beam Parameter

The beam radius and the radius of curvature can conveniently be combined into a single complex beam parameter q, defined using the confocal distance as

$$q = z + iz_c. \tag{11}$$

It is apparent that q is purely imaginary at the beam waist. Taking the reciprocal, we find

$$1/q = 1/R - i\lambda/\pi w^2. \tag{12}$$

Using the two definitions of q, it is straightforward to solve for the useful inverse relations which allow determination of the waist radius and distance from the waist, if we are given the beam radius and radius of curvature measured at a point along the axis of propagation:

$$\begin{aligned} w_o &= w/[1 + (\pi w^2/\lambda R)^2]^{0.5} \\ z &= R/[1 + (\lambda R/\pi w^2)^2]. \end{aligned} \tag{13}$$

In the geometrical optics limit $\lambda \to 0$, we see that $1/q \to 1/R$, and q is equal to the radius of curvature. In taking this limit of (11), we keep θ_0 constant to obtain $z_c \to 0$. Thus, we also obtain that, in the geometrical optics limit, the radius of curvature varies linearly with distance from the waist (focus).

E. Ray Matrices and Gaussian Beam Propagation

The similarity between the complex beam parameter of a Gaussian beam and the radius of curvature of a geometrical optics beam suggests that systems can be analyzed in terms of their effect on q in a manner analogous to the treatment of rays in a linear geometrical optics system. In this approach, the location and slope of the ray at the output plane of a paraxial system are defined to be linear functions of the parameters of the input ray. The term *system* here represents anything from the most simple element such as an interface between two media to a complete multielement system. Denoting the position as r and the slope as r', we obtain

$$\begin{aligned} r_{out} &= A \cdot r_{in} + B \cdot r'_{in} \\ r'_{out} &= C \cdot r_{in} + D \cdot r'_{in}. \end{aligned} \tag{14}$$

Note that r' here represents the actual slope of rays, rather than the reduced slope as considered in [14]. Treating the ray position and slope as a column matrix, the effect of the system element can be written

$$\begin{bmatrix} r_{out} \\ r'_{out} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} r_{in} \\ r'_{in} \end{bmatrix}. \tag{15}$$

A succession of elements is handled by multiplication of the appropriate 2 by 2 matrices to find the overall system matrix. Since the radius of curvature is defined by $R = position/slope$, we can combine the two parts of the previous equation into a relationship for the radius of curvature:

$$R_{out} = (A \cdot R_{in} + B)/(C \cdot R_{in} + D). \tag{16}$$

The extension of this ray transformation approach to Gaussian beams leads to the $ABCD$ law [15], [16], in which the four parameters characterizing an optical system element operate on the complex radius of curvature in a manner similar to (16), giving

$$q_{out} = (A \cdot q_{in} + B)/(C \cdot q_{in} + D). \tag{17}$$

The parameters A, B, C, and D are the same as for the geometrical optical system element.

The $ABCD$ law is an enormous aid to Gaussian beam calculations since all of the theory of a geometrical optics system operating on rays can be taken over. We obtain the matrix for a sequence of elements by multiplying the individual $ABCD$ matrices, starting with that for the first element encountered by the beam and adding the matrix for each subsequent element on the left. We obtain the complex beam parameter at the system output (or at any point within the system) using (17), and find w and R using

$$\begin{aligned} w &= [-\lambda/(\pi \cdot \mathrm{Im}\,(1/q))]^{0.5} \\ R &= [\mathrm{Re}\,(1/q)]^{-1}. \end{aligned} \tag{18}$$

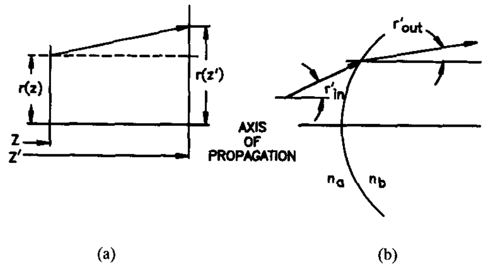

Fig. 2. (a) Propagation of a ray from z to z' in free space; the slope is unchanged. (b) Refraction of a ray at curved interface between regions having different indexes of refraction.

The wavelength of the radiation in the relevant medium must be used with (18).

The most basic ray matrix is that for a distance L of propagation in a uniform material of index of refraction n : this changes the offset of the ray from the axis by an amount proportional to r'_{in} , but does not change the ray's slope. With the definitions used here this is as given in Table 1, irrespective of the index of refraction [14]. A second fundamental ray matrix is that for an interface between media of different indices of refraction. We assume in general that the interface has radius of curvature R, but in the paraxial limit we take the refraction to be occurring in a plane defined by the intersection of the interface with the axis of propagation of the beam. Passage through an interface changes the slope of a ray, but does not affect its position. These two situations are illustrated in Fig. 2. A "thin lens" is a focusing element which consists of one or two curved interfaces, but with physical separation neglected. Its matrix can be found by multiplication of the matrix for the first surface by that for the second surface. To obtain the matrix for a "thick lens," we include the distance between the interfaces, but neglect the distance change produced by the curvature of the boundaries. A spherical mirror of radius of curvature R is equivalent to a thin lens of focal length $f = R/2$. Ray matrices and the ABCD law are discussed in [7] and [15]–[18]. Some examples of ray matrices are given in Table 1 and additional ray matrices are given in these references.

F. Gaussian Beam Transformation with Focusing Elements

Transformation of Gaussian beams is of particular importance in quasi-optical system design since one generally must keep beams from growing excessively. In simple paraxial theory focusing elements are analogous to "thin" lenses in traditional optics terminology and change the radius of curvature of the beam without affecting the beam radius, as implied by the matrix given in Table 1. This is a property of thin lenses but can be applied with reasonable accuracy to realistic lenses [19], [20]. While an ideal focusing mirror can be treated as a thin lens, a real mirror used in an off-axis configuration, especially if it has a small focal ratio, can create significant beam distortion and cross polarization [21], [22].

Table 1 Examples of Ray Matrices

Element	Ray Matrix
Distance L in uniform medium	$\begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$
Curved interface from refractive index n_a to n_b; $R > 0$ if concave to left	$\begin{bmatrix} 1 & 0 \\ \frac{n_b - n_a}{n_b R} & \frac{n_a}{n_b} \end{bmatrix}$
Thin lens of focal length f	$\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$
For a thin lens of index n_2 embedded in n_1 with first surface R_2 and second surface R_1: $1/f = [(n_2 - n_1)/n_1] \cdot [1/R_2 - 1/R_1]$. For spherical mirror of radius of curvature R: $1/f = 2/R$.	
Slab of thickness L index n_2 embedded in n_1	$\begin{bmatrix} 1 & (n_1/n_2) \cdot L \\ 0 & 1 \end{bmatrix}$
Thick lens with first surface R_1 and second surface R_2; thickness d of index n_2 embedded in n_1	$\begin{bmatrix} 1 + (n_2 - n_1)d/n_2 R_1 & n_1 d/n_2 \\ -1/f - d(n_2 - n_1)^2/n_1 n_2 R_1 R_2 & 1 + (n_1 - n_2)d/n_2 R_2 \end{bmatrix}$
$1/f = [(n_2 - n_1)/n_1] \cdot [1/R_2 - 1/R_1]$	
Pair of thin lenses, first f_1 and then f_2, separated by sum of their focal lengths	$\begin{bmatrix} -f_2/f_1 & f_1 + f_2 \\ 0 & -f_1/f_2 \end{bmatrix}$

The general beam transformation properties of a quasi-optical system can be found from the $ABCD$ law and the requirement that q be purely imaginary at the beam waist. The situation illustrated in Fig. 3 consists of a waist at input distance d_{in} from the input plane of a system having an $ABCD$ matrix defined in terms of transformation from input plane to output plane. We find the complex beam parameter from the matrix $\boldsymbol{M}$, which represents propagation through distance d_{in}, transformation by the system, and finally propagation through a distance d_{out} as described above:

$$\begin{aligned} \boldsymbol{M} &= \begin{bmatrix} 1 & d_{out} \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} 1 & d_{in} \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} A + Cd_{out} & Ad_{in} + B + d_{out}(Cd_{in} + D) \\ C & Cd_{in} + D \end{bmatrix}. \end{aligned} \tag{19}$$

Taking $q_{in} = iz_c$ yields

$$q_{out} = \frac{(A + Cd_{out})iz_c + [(A + Cd_{out})d_{in} + (B + Dd_{out})]}{Ciz_c + Cd_{in} + D}. \tag{20}$$

Solving for the real part, we obtain the distance from the system output plane to the output beam waist and the output waist radius:

$$d_{out} = \frac{(Ad_{in} + B)(Cd_{in} + D) + ACz_c^2}{(Cd_{in} + D)^2 + C^2 z_c^2} \tag{21a}$$

$$w_{o\ out} = \frac{w_{o\ in}}{[(Cd_{in} + D)^2 + C^2 z_c^2]^{0.5}} \tag{21b}$$

Probably the most important specific example of Gaussian beam transformation formulas is that of a thin lens, whose $ABCD$ matrix is given in Table 1. The results

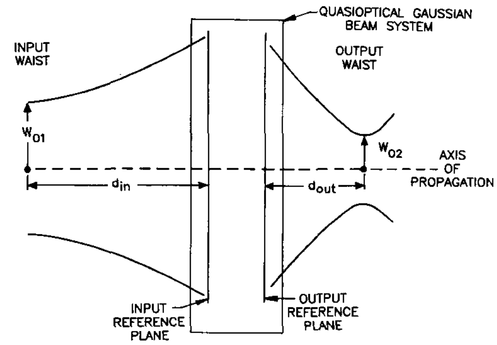

Fig. 3. Transformation of Gaussian beam by general quasi-optical Gaussian beam system indicating sizes and locations of input and output waists.

obtained by substitution in the preceding equations can be written conveniently as

$$d_{out} = f \cdot \left[1 + \frac{d_{in}/f - 1}{(d_{in}/f - 1)^2 + z_c^2/f^2}\right] \quad \text{(22a)}$$

$$w_{o\ out} = \frac{w_{o\ in}}{[(d_{in}/f - 1)^2 + z_c^2/f^2]^{0.5}}. \quad \text{(22b)}$$

This pair of equations describes the well-known transformation properties of a thin lens operating on a Gaussian beam, and the results are illustrated in Fig. 4. For $d_{in} = f$ we always have $d_{out} = f$, and also obtain the maximum value of the magnification $M = w_{o\ out}/w_{o\ in}$; $M \max = f/z_c$. For a given input waist radius this also gives the maximum output waist radius $[w_{o\ out}]\max = \lambda f/\pi w_{o\ in}$. From (20) we see that the beam radius at $d_{out} = f$ is **always** equal to this same value, but it is a beam waist only for $d_{in} = f$. The case of a pair of focusing elements separated by the sum of their focal lengths deserves particular attention since, from the $ABCD$ matrix given in Table 1, we find two interesting properties: $w_{o\ out} = (f_2/f_1) \cdot w_{o\ in}$, irrespective of d_{in} and λ, and d_{out} depends only on d_{in} and is equal to f_2 for $d_{in} = f_1$. The transformation properties of this "Gaussian beam telescope" are thus wavelength-independent, making this a very useful system element for broadband systems [4], [23]. A variety of other Gaussian beam transformation formulas have been developed which are useful for designing optics to transform a specific Gaussian beam with a waist at a particular location to another beam having specified parameters [7], [24].

The transformation of a Gaussian beam by a focusing element can also be understood in terms of modification of the phase distribution transverse to the axis of propagation. An ideal focusing element of focal length f produces a quadratic phase variation

$$\Delta\phi(r) = \pi r^2/\lambda f. \quad (23)$$

When combined with the input beam given by (6) and the assumption that the beam radius is unaffected, the pair of equations (22) is obtained [25]. Starting with the complex beam parameter q, it is apparent that the propagation of

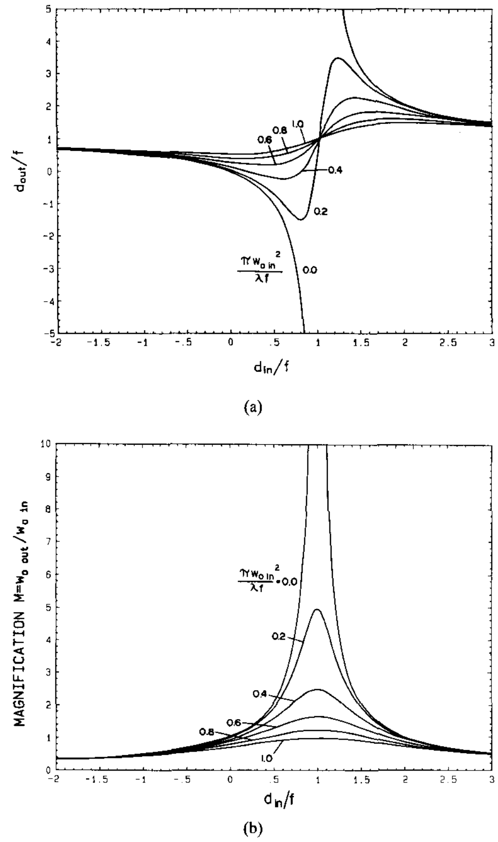

Fig. 4. (a) Gaussian beam transformation by thin lens showing output waist distance as function of input waist distance and input beam parameter $\pi w_o^2/\lambda f = z_c/f$. (b) Magnification of Gaussian beam as function of input distance and input beam parameter.

a Gaussian beam can be represented in terms of motion on a complex circle diagram or Smith chart; with this formalism, beam transformation by a thin lens is analogous to impedance transformation through a lossless, reciprocal, two-port network [26]. This is convenient, but direct solution of the transformation and matching equations is more widely used.

There does not seem to have been adequate detailed work devoted to optimization of focusing elements for quasi-optical Gaussian beam systems. Several studies have investigated the performance of lenses designed using geometrical optics, using hybrid analyses employing combinations of ray tracing and diffraction calculations [19], [20]. The differences found could be significant in specific applications. Further efforts in this area are desirable to improve quasi-optical system performance as well as design accuracy.

G. Truncation of Gaussian Beams

All of the previous discussion is based on the assumption that the Gaussian beam and any focusing elements are infinite in extent transverse to the axis of propagation. This cannot be the case for a realistic system, and we must therefore consider the effects of beam truncation. Once truncation has destroyed the perfectly Gaussian nature of the field distribution, the simple expressions for Gaussian beam propagation no longer apply, and near-field or far-field diffraction calculations must be carried out. The truncation level can be expressed in terms of the distance from the axis in units of the beam radius at which the truncation occurs, e.g. $r_t = \alpha w$, or as the fraction of power outside the truncation radius. For the fundamental Gaussian beam, the fraction of power outside radius r_t is given by

$$f_{out} = \exp[-2(r_t/w)^2]. \tag{24}$$

The far-field pattern of a Gaussian beam with appreciable truncation at its waist exhibits side lobes [27]. It also diverges more rapidly than the untruncated beam, which can be expressed in terms of a smaller effective waist radius given by [28]:

$$w_{o\ eff} = w_o[1 - f_{out}^{0.5}]. \tag{25}$$

The behavior in the near field is more complex [29], and it is difficult to generalize other than that the non-Gaussian component can vary with distance from truncation plane, and with truncation level. Truncation which takes place elsewhere than at the plane of the beam waist generally results in non-Gaussian component, and can increase or decrease the beam divergence [28]. The modification of the radius of curvature and effective beam waist radius produced by truncation of the Gaussian beam produces a shift in location of subsequent beam waist(s) produced in a quasi-optical system. This effect can be relatively more harmful than the fractional power lost immediately by the truncation as given by (25). For these reasons, a relatively conservative criterion is that the diameter required for clearance of a Gaussian beam is $D = 4 \cdot w$, corresponding to truncation at the -35 dB level and $f_{out} = 3 \cdot 10^{-4}$ [28]. In applications where the effect of beam waist change and shift is less important, a clearance diameter $D = 3 \cdot w$, which corresponds to truncation at the -20 dB level and $f_{out} = 0.011$, can be satisfactory [20].

III. Launching and Coupling Gaussian Beams

A. Gaussian Beams from Feed Horns and Radiating Systems

The importance of Gaussian beams, and the fundamental Gaussian mode in particular, is greatly increased by the high degree to which this relatively simple form represents the radiation pattern of different types of feed horns. These are critical elements for coupling to guided wave devices such as mixers and detectors. The analysis of radiation patterns in terms of Gaussian modes is carried out by expanding the electric field in the horn aperture in terms of a set of Gauss–Hermite or Gauss–Laguerre functions. If many modes are required to reproduce the aperture distribution, the Gaussian mode approach may be a useful computational tool, albeit not an extremely simple one. Only if the fraction of the power in the fundamental mode is large will we be able to satisfactorily represent the radiation pattern in terms of a single Gaussian mode.

Corrugated or scalar feed horns are widely used at millimeter wavelengths, and have an aperture field distribution which ideally is of the form $J_o(\alpha r/a)$, where $\alpha \cong 2.405$ and a is the aperture radius [30]. Since this Bessel function is quite similar to $\exp[-(r/w)^2]$, we expect the fundamental Gaussian mode **alone** to be a good representation of the aperture field. Indeed, for $w/a = 0.64$, we find that 0.98 of the power radiated is in the fundamental mode [31], [32]. Real feed horns have finite length, so that the equiphase surface of the electric field at the horn aperture is a spherical cap of radius of curvature R, taken to be equal to the slant length of the horn, L_s. Knowing R and w, it is straightforward to determine the size and location of the Gaussian beam waist using (13). This approach provides useful guidelines for designs using scalar feed horns [33], although for very accurate calculations the fundamental mode alone may be inadequate [34]. The field distribution in hollow dielectric waveguides is quite similar to that in corrugated metal waveguides. Analysis of dielectric waveguide radiation patterns in terms of Gaussian modes [35] has thus given results essentially identical to those for scalar feed horns, while recent treatments [36] give only slightly different results.

The situation for several types of horns used at millimeter wavelengths has been summarized in [37]. In Table 2 we present a summary of fundamental Gaussian mode results for some commonly used types of feed horns. The beam radius given, w_{opt}, is the value which maximizes the coupling to the fundamental Gaussian mode. Note that this is NOT the beam waist radius, but rather the radius fitted to the aperture field distribution—the waist radius can be obtained from w_{opt} and the radius of curvature as described above. The polarization efficiency is the fraction of power radiated in a linearly polarized beam assuming linearly polarized excitation; the coupling efficiency is the fraction of power radiated into a fundamental Gaussian mode characterized by w_{opt} and $R = L_s$, including polarization loss. A Gaussian beam is largely confined to a region of diameter $D \approx 3 \cdot w$ so that it is apparent that feed horns with tapered field distributions will be characterized by a beam radius $\approx 1/3$·aperture diameter.

For feedhorns with asymmetric aperture field distribution *and/or* aperture dimensions, allowing for an asymmetric fundamental-mode beam does slightly increase the fraction of power radiated in the fundamental Gaussian mode. This is not an unrealistic approach, since an asymmetrical Gaussian beam propagates in the same manner as a symmetric one. The only distinction is that it has different waist radii and waist locations for the two planes perpendicular to the axis of propagation. Gaussian beam transformation is independently evaluated for the two orthogonal planes and the pattern of a conical feedhorn [41] can, for example, be symmetrized by the proper astigmatic optical system [24]. General apertures are analyzed in terms of Gaussian modes

Table 2 Gaussian Beam Radius and Coupling Efficiency for Different Feed Horns

Feed Horn Type[1]	Optimum Beam Radius[2]	ϵ_{pol}	ϵ_{coup}
Scalar (HE_{11})	0.32	1.00	0.98
Circular (TE_{11})	0.38	0.96	0.91
Circular (TE_{11})[3]	0.32; 0.44	0.96	0.93
Square (uniform)	0.51	1.00	0.79
Square (TE_{10})[4]	0.35; 0.51	1.00	0.88
Rectangular (TE_{10})	0.30	1.00	0.85
Rectangular (TE_{10})	0.35; 0.25	1.00	0.88
Diagonal[5]	0.43	0.92	0.84
Cube-Corner[6]	1.24λ		0.78

[1]Circular horns are assumed to have unit diameter, the diagonal and square horns are assumed to have unit square apertures, and the rectangular horn is assumed to have a 2:1 aspect ratio with unit dimension perpendicular to the electric field direction and dimension 0.5 parallel to the field direction.

[2]The optimum beam radius is expressed as a fraction of the unit dimension. Where a single value is given, a symmetric Gaussian beam has been assumed, and where two values are given, a beam with independent values of w in two orthogonal coordinates has been used. The first value applies to the axis perpendicular to the electric field direction on the horn axis, and the second applies to the axis parallel to the axial field direction.

[3]The analysis here is different from that of Murphy [38], who used Gauss–Laguerre modes rather than an asymmetric fundamental mode Gaussian.

[4]We see that for a TE_{10} horn to have a best-fit fundamental-mode Gaussian beam which is symmetric, its aperture dimensions should be in the ratio 1.46:1.

[5]The diagonal feed horn is assumed to have aperture field given by combination of TE_{10} mode components; the results given here are from Johansson *et al.* [39].

[6]The results for cube-corner antenna are for a modified design having whisker length $L = 1.35\lambda$ and separation from vertex $d = 0.9\lambda$ as described by Grossman [40].

in [42]. Dual-mode or Potter horns [43] are almost identical to corrugated feed horns over their useful bandwidth. Planar patch, dipole, bow-tie, slot, and spiral antennas as well as various types of end-fire slot antennas are now being widely developed for millimeter and submillimeter wavelengths [44], but the Gaussian beam analysis of such antennas remains to be carried out.

B. Coupling and Misalignment of Gaussian Beams

In order to be able to design and to fix tolerances in quasioptical systems, we must consider the problem of imperfect coupling between different Gaussian beams. This situation can result from imperfect match between the beam radiated by one component and that accepted by another, and by misalignments or offsets between the ideal and actual beam propagating in a system. This issue has been covered quite thoroughly by Kogelnik [45], and we here summarize only the results for fundamental-mode beams.

As illustrated in Fig. 5, we consider the coupling between two fundamental-mode Gaussian beams a and b, which are

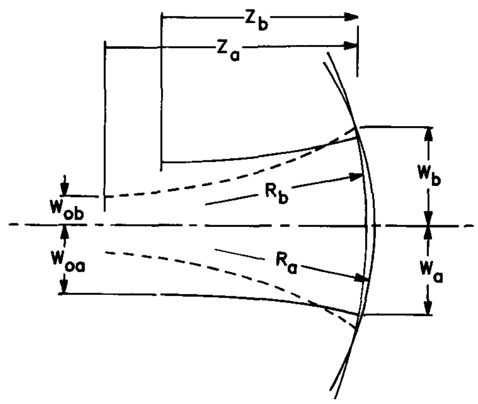

Fig. 5. Schematic of coupling between two Gaussian beams a and b.

assumed to be coaxial, but with possibly different-sized and separated waist radii. The field coupling coefficient is obtained from the overlap integral between the two field distributions given by (6), and since we are considering beams with azimuthal symmetry, we can express this as an integral only over r:

$$c_{ab} = \int_0^\infty u_a^* u_b \cdot 2\pi r dr. \tag{26}$$

It is convenient to write the expression for the Gaussian beams using q (12), giving us

$$u(r) = [2/\pi w^2]^{0.5} \exp(-i\pi r^2[1/q]) \cdot \exp(i[\phi - kz]). \tag{27}$$

Defining $\Delta\phi = \phi_b - \phi_a$ and $\Delta z = z_b - z_a$, we find that

$$c_{ab} = \frac{2i\lambda}{\pi w_a w_b}(1/q_{a^*} - 1/q_b)^{-1} \cdot \exp[i(\Delta\phi - k\Delta z)]. \tag{28}$$

The power coupling coefficient is given by

$$K_{ab} = |c_{ab}|^2, \tag{29}$$

which yields

$$K_{ab} = \frac{4}{(\pi w_a w_b/\lambda)^2 \cdot (1/R_a - 1/R_b)^2 + (w_a/w_b + w_b/w_a)^2}. \tag{30}$$

Using the alternative definition of q from (11), the power coupling coefficient can be expressed in terms of the beam waist radii and distance between the waists as

$$K_{ab} = \frac{4}{(\lambda/\pi w_{o\,a} w_{o\,b})^2 \cdot \Delta z^2 + (w_{o\,a}/w_{o\,b} + w_{o\,b}/w_{o\,a})^2}. \tag{31}$$

To obtain perfect coupling, we need to match beam radius and radius of curvature or, equivalently, to have the two waists be coincident and have equal waist radii.

Interferometers, which operate on the principle of having different path lengths for two or more beams derived from a single beam, are limited in performance by imperfect beam overlap and are further discussed in subsection IV-B.

Imperfect coupling can also result from lateral offset of the two beams, which can be the result of alignment errors or from propagation of a Gaussian beam in an interferometer at nonnormal incidence; this problem becomes more severe as beam waists are made smaller. A relative tilt of the axes of propagation is generally a result of errors in system alignment, which is increasingly a problem as beam waists are made larger, and the beam divergence is reduced. These situations can be analyzed by evaluating appropriate overlap integrals as described in [45]. A more complete treatment of coupling and conversion between modes in terms of a multimode scattering matrix formalism has been developed by Padman and Murphy [46], which allows for beam truncation as well as certain misalignments; this approach may be extended to include other situations at the expense of considering additional modes.

IV. Quasi-Optical Components and Instruments

Quasi-optical components have been described in a number of reviews on the topic [47] as well as being covered in several reviews of quasi-optical propagation in general [3], [4]. We summarize here some of the components that have seen significant use in quasi-optical systems developed in recent years.

A. Polarization Processing

The Gaussian beam can have any polarization state; consequently quasi-optical components for transforming between polarization states play an important role in many systems. Probably the most basic is the wire grid polarizer. As has been known since the experiments of Hertz [5], an array of conducting wires with spacing less than a half wavelength will reflect the component of the electric field parallel to the wires and transmit the orthogonal linear component. Wire grid polarizers in quasi-optical systems serve as polarization dividers and combiners for linearly polarized radiation, as well as extracting the linearly polarized components from arbitrarily polarized signals. Wire grid polarizers have been extensively analyzed—the literature is so vast that it is impossible here to do more than indicate some reviews and references which focus on wire grids used for polarization diplexing [48], together with a selection of more general analyses [49]. Wire grid polarizers are among the most ideal components in the millimeter range, with virtually unmeasurable loss, while at submillimeter wavelengths their loss increases because of the greater absorption in the conductors. A sequence of polarizing grids can be used to rotate the direction of linearly polarized radiation with very low loss over a considerable bandwidth, as discussed by Amitay and Saleh [50]. Free-standing wire grids produce essentially no distortion of the propagating Gaussian beam, while the substrate material on dielectric-supported grids is generally so thin that it has only a small effect on the amplitude of the transmitted and reflected radiation, while leaving the Gaussian beam properties essentially unaffected.

Wave plates produce a differential phase shift between the components of linearly polarized radiation. A quarter-wave plate produces a 90° differential phase shift, and thus can transform linearly polarized radiation into circular polarization and vice versa. A half-wave plate produces a 180° differential phase shift and can be used to rotate the plane of polarization of a linearly polarized beam. These components can be made using natural or artificial anisotropic dielectrics, metal plates forming arrays of waveguides, and by polarization division and processing of a beam. Reviews of different designs and some recent developments are given in [51]. The loss of wave plates and their effects on Gaussian beam propagation are generally small. Some samples of often-used materials, including many plastics, have significant anisotropy. Variations in dielectric properties, both real and those resulting from measurement errors, have been a real hindrance to millimeter and submillimeter system design; an interesting analysis and intercomparison of materials is given in [52].

B. Filters and Diplexers

A wide variety of quasi-optical filters has been developed for different applications. For convenience we divide these into four major categories: two-dimensional structures, three-dimensional structures, dual-beam interferometers, and multibeam interferometers. These are illustrated schematically in Figure 6.

In the first category we place single-plane structures which interact with a propagating beam by virtue of a pattern of conductors which is periodic in two dimensions. This includes basic geometries such as strips or wires oriented parallel to the electric field, but with conductor spacing $> \lambda/2$. These act as high-pass filters in transmission. A symmetric two-dimensional array of wires performs the same function for an arbitrarily polarized incident beam. By virtue of Babinet's principle [53], complementary structures, obtained by interchanging conducting and nonconducting regions, have transmission functions which are the reflection functions of the original structures. Thus, an array of conducting patches acts as a low-pass filter in transmission. A very extensive literature exists on the behavior of different geometries which exhibit resonant behavior. Examples include rings [54], circular slots [55], crosses [56], tripoles [57], and gridded squares [58], as well as more complex geometries [59]. High-T_c superconductors have also been employed with a significant improvement in the Q factor [60]. The frequency dependence of complex structures must be calculated using more complex methods of analysis [61].

The second category of filters includes three-dimensional structures which are periodic in two dimensions but which have arbitrary extent in the third dimension. This category includes arrays of waveguides, also called perforated plates or dichroic plates. Each individual waveguide exhibits a low-frequency cutoff, which is retained as a property of

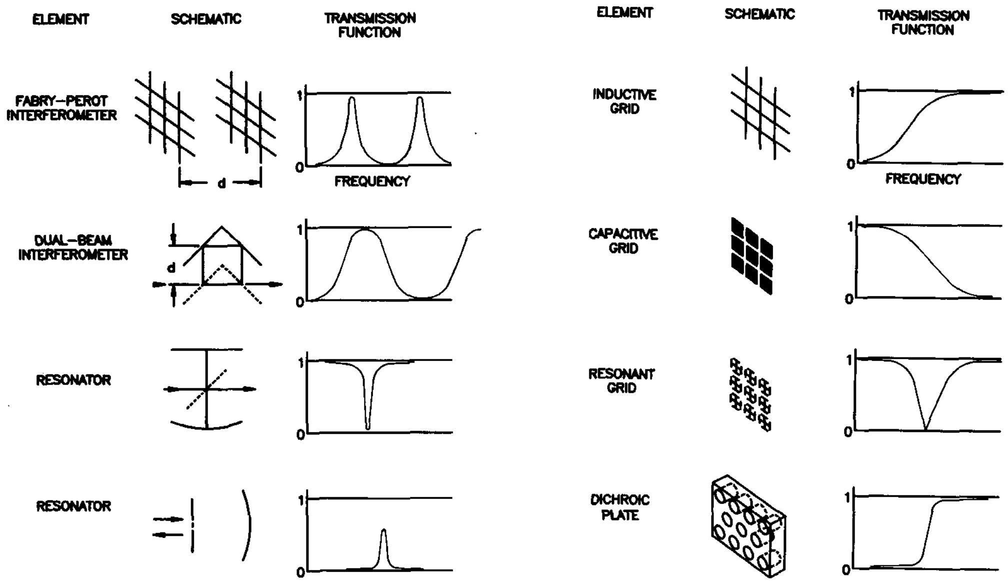

Fig. 6. Different frequency selective devices with their transmission functions.

the array, so that it functions as a high-pass filter in transmission [62], [63]. Dichroic plates can be directly machined at longer wavelengths, and have been made by electroplating in the submillimeter region [64]. The flexibility afforded by this method of fabrication allows the use of asymmetric apertures, permitting dichroic plates to be used at larger (45°) angles of incidence than the $\cong 20°$ limit for conventional dichroic plates.

Dual-beam interferometers are derivatives of the Michelson interferometer widely used at optical and infrared wavelengths. The basic principle is to divide the incident beam into two parts, delay one beam relative to the other, and then recombine the beams. The frequency dependence of the interferometer is a sinusoid determined by the path length difference. The division of the input into two beams can be achieved by amplitude division using a dielectric slab [65], by specific polarization-independent means [66], or by polarization division with a wire grid. In the last case, the relative direction of linear polarization of the two beams must be rotated, leading to the name polarization-rotating interferometer [67]. In addition to use as an interferometer for spectroscopy, Martin–Puplett polarization rotating interferometers are widely employed as filters, and as diplexers for combining signal and local oscillator into a single beam to a mixer [68].

The performance of the dual-beam interferometer is limited by the overlap between the beams, which, although having started with a common waist radius, have traveled different distances from that waist when they are recombined. Imperfect beam overlap will decrease the amplitude of the transmission maxima and increase the amplitude of the minima [69]. A second issue is that of the growth of the beams, which sets a lower limit on the clear aperture required for the interferometer, and thus on its overall size. A trade-off between these constraints is necessary to determine the minimum size device required to achieve a specified loss and frequency response periodicity [4]. Dual-beam diplexers, especially the polarization rotating variety, have attained remarkably low loss, typically only a few tenths of a dB at frequencies approaching 1000 GHz.

Multibeam interferometers are based on repeated reflections between partially reflecting mirrors, and are generally called Fabry–Perot interferometers, or FPI's. Their response (the Airy function) depends on the reflectivity of the mirrors as well as their separation, which gives additional flexibility in obtaining a particular frequency dependence. The price that is paid is that the output beam consists of the sum of many partial beams which have traveled a set of different distances from their original beam waist. The calculation of the response is more difficult than for the simple two-beam overlap in the dual-beam interferometer, and the loss caused by imperfect beam overlap can be more of a problem owing to the additional path length difference [70].

If a FPI with plane mirrors is tilted relative to the incident beam direction, as is necessary to have access to reflected, transmitted, and incident beams for use as a diplexer [71], the beam will suffer geometrical walk-off on each successive reflection, which is equivalent to a lateral offset between the partial Gaussian beams from each pass through the interferometer [70]. This again reduces the overlap between the beams and degrades the performance of the FPI. Walk-off loss can be reduced by filling the space between the mirrors of a FPI with a dielectric [72], but absorption must then be considered. Walk-off can be eliminated by using a ring geometry, which can employ refocusing mirrors to eliminate beam growth as well [73]. The loss due to walk-off can also be avoided by using polarization rotation to allow all beams to interact with the FPI at normal incidence [74]. These different types of FPI diplexers have demonstrated losses less than 0.5 dB at frequencies up to several hundred GHz.

The mirrors of a FPI can consist of dielectric slabs or planar structures as discussed above. Wire grids with spacing $\geq \lambda/2$ can be used to obtain partial reflection, but more often two-dimensional mesh is employed. A Fabry–Perot interferometer has been described by Tudisco which employs wire grids with different orientations as the partial reflectors. This results in a more complex behavior, since no single polarization state describes the electric field in the interferometer, but allows changing the mirror reflectivity with relative ease [75]. An interferometer developed by Erickson has some of the characteristics of a FPI combined with those of a polarization-rotating interferometer [76].

Quasi-optical multisection filters can be considered an extension of multibeam interferometers discussed previously, in that a succession of dielectric slabs and partially reflecting planar structures are used to create the desired frequency response [77]. The analysis of such complex components has generally been carried out assuming plane wave rather than Gaussian beam excitation. While multisection filters offer great flexibility, incorporation of more rigorous quasi-optical design principles would enhance the ability to accurately predict loss and frequency response in realistic use.

A frequency-selective device which has not seen widespread use but which offers interesting potential is the diffraction grating, used to measure wavelengths in the millimeter range as early as 1948 [78]. Experiments have shown that blazed gratings can achieve efficiencies in excess of 90%, so that gratings may play useful roles as diplexers and also as low-resolution spectrometers, especially where high power levels are involved [79].

C. Quasi-Optical Ferrite Devices

Ferrite devices carry out important functions as isolators, circulators, and duplexers (separating transmitted and received signals in radar systems). Propagation in a quasi-optical ferrite is in fact simpler than in waveguide or other guided-wave structure, because as long as the diameter of the ferrite is large enough that truncation effects can be neglected, propagation of a Gaussian beam can be considered to be taking place in an infinite medium. The spins of the ferrite material are oriented by a magnetic field which is aligned with the axis of propagation of the beam. The interaction of the magnetic field of the radiation with the spins results in Faraday rotation of the direction of linear polarization of a quasi-optical beam propagating through the ferrite [80]. The rotation angle per unit thickness of the ferrite is determined by properties of the ferrite; at

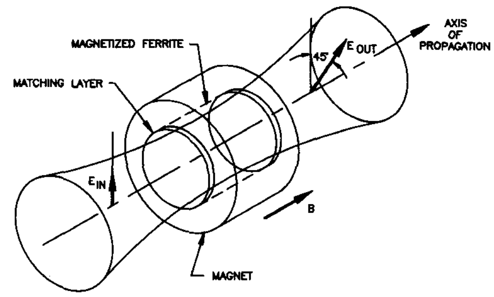

Fig. 7. Propagation of Gaussian beam through quasi-optical ferrite indicating rotation of direction of linear polarization.

millimeter wavelengths the rotation angle is essentially independent of frequency, allowing very broadband rotation isolators to be made. The critical feature is that the sense of rotation is fixed relative to the magnetic field direction, and not to the direction of propagation. Thus, we can obtain a nonreciprocal device which, as shown schematically in Fig. 7, has very low loss for propagation in one direction while discriminating strongly (typically by a factor > 100) against propagation in the reverse direction.

Gaussian beam propagation in the magnetized ferrite can be analyzed ignoring the effect on the polarization, and the primary characteristic is that of a material with relatively high dielectric constant which reduces beam growth (thus making it easier to avoid truncation loss). To achieve good performance, the faces of the isolator must have an antireflection coating, which does limit the bandwidth that can be obtained. A quasi-optical ferrite isolator with less than 0.1 dB loss and greater than 40 dB isolation in the 33–39 GHz range has been reported, 0.5 dB over 20 GHz in the 94 GHz range has been achieved, and a quasi-optical ferrite isolator at 285 GHz with insertion loss typically 2 dB has been developed [81].

D. Resonators

A quasi-optical resonator is a system for which the propagating beam returns to its original state (beam radius and radius of curvature) after passing through it. As for multibeam interferometers, the large number of periodic interactions allows resonators to have a well-defined set of resonant frequencies together with strong discrimination against other frequencies. Since diffraction causes the beam to grow, a resonator must employ at least one focusing element. This is the major difference between resonators and interferometers previously discussed. As work on resonators was one of the driving forces behind the development of Gaussian beam theory, the basic theory of operation of resonators was developed quite early [6], [7], while the limits and accuracy of approximate Gaussian beam theory have been investigated more recently [82].

The most basic resonator consists of two reflecting mirrors, and a round trip consists of a beam reflecting from each while making a complete trip along the resonator axis.

There are many variations on the basic resonator design, including systems having more than two refocusing mirrors [83]. Input and output coupling has been achieved by small apertures in otherwise highly reflecting mirrors [84], partially reflective films within the resonator [85], [86], and partially reflective mirrors [87]. The general basis for resonator analysis is to ignore spillover past the resonator mirrors, define the $ABCD$ matrix for a complete pass through the resonator, and demand that the output beam be identical to the input beam. It is conceptually convenient to unfold the resonator into a sequence of focusing elements separated by distances of free space. For a two-mirror resonator, for example, we define the distance from the beam waist to the first reflector having radius of curvature R_1 to be d_1, the mirror separation to be d, and the second reflector to have radius of curvature R_2; the $ABCD$ matrix for the resonator is found from the cascade product of the individual element matrices as defined in Table 1.

The general condition to obtain the parameters of the fundamental mode of the resonator is obtained using the complex beam parameter q defined in (11) and (12), together with the $ABCD$ law (17) and demanding that $q_{out} = q_{in}$. This provides the relationship

$$q = (A - D)/2C \pm (i/2C) \cdot [4 - (A + D)^2]^{0.5}. \quad (32)$$

The beam waist is defined by the requirement that q be purely imaginary there. This yields $A = D$, and this gives us the location of the beam waist and the waist radius. The results for different types of two-mirror resonators are given in [7], but more complex systems are readily treated by the same method. The resonant frequencies f_o are determined by the requirement that the round-trip phase shift through the resonator defined by (6) and (7) be an integral multiple of π. The Q, defined as $f_o/\Delta f$ where Δf is the 3 dB width of the frequency response function, of resonators in the 100–300 GHz range can approach 10^6 [85]. This makes these components extremely valuable for spectroscopy [83], [84], materials measurement [2], [88], stabilization of oscillator frequency [89], and power combining of multiple oscillators (discussed separately below), as well as other functions.

E. Quasi-Optical Power Combining

The limited power output of solid-state fundamental oscillators and frequency-multiplied sources throughout the terahertz range makes the possibility of coherently combining the outputs of multiple oscillators extremely attractive. The low loss and flexibility of quasi-optical propagation has focused considerable attention on the development of quasi-optical power combiners in recent years [90], with the result that a wide variety of designs have been developed and used at frequencies up to 100 GHz [91].

The quasi-optical resonator plays a key role in one category of quasi-optical power combiners by coupling the power from each oscillator into a single spatial mode and by synchronizing the oscillation of the individual elements through the feedback from the resonator mode to the antenna element associated with each oscillator. To date, only a modest number of elements have been employed using the resonator approach, but the results have been quite encouraging and should be extendable to larger numbers of devices, especially if they can be fabricated as monolithic arrays. Quasi-optical power combining should allow solid-state millimeter sources with several watts of power to be produced in the relatively near future.

Quasi-optical power combiners not employing resonators have also been constructed. These have generally employed coupling between circuit elements, either the oscillating devices themselves [92] or planar antennas [93], to achieve synchronization. These experiments have so far been restricted to relatively low microwave frequencies, but up to 100 active elements have been employed. A more complete discussion of this topic can be found in the article by R. M. Weikle *et al.* in this issue.

F. Other Quasi-Optical Components

The reviews of quasi-optical components together with the preceding discussion give some idea of the wide range of quasi-optical components that have been developed. Here we will touch on some relatively recent developments that indicate the breadth of current developments.

In addition to power combining of sources, quasi optics is utilized in several types of multipliers to extend the frequency range of solid-state sources. While the nonlinear multiplier itself described in [63] is constructed in waveguide, quasi-optical tuning elements are employed for impedance matching. A more purely optical approach utilizes a two-dimensional array of nonlinear elements. This approach has obvious advantages in terms of power handling capability and should also be capable of high efficiency. Power is coupled in and out quasi-optically, with dichroic plates or other types of filters used to separate input and output frequencies and dielectric slab tuning elements employed to optimize performance. A conversion efficiency of 9.5% doubling to 66 GHz and an output power of 0.5 W (pulsed) have been reported for an array utilizing 760 Schottky varactor diodes [94]. Utilization of nonlinear devices having appropriate symmetry can enhance production of odd harmonics [95]. This approach appears to have considerable potential, especially when coupled with high output power-combined source.

Arrays of planar devices have a variety of other uses in quasi-optical systems. A quasi-optical grid amplifier has been developed using 50 MESFET devices [96] which, although operating at only 3.3 GHz frequency, illustrates a technique that should be applicable at higher frequencies. The voltage-variable phase shift of an array of varactor diodes makes this an attractive approach for beam steering [97], while an array of PIN diodes can be employed as a switch. All of these applications naturally are favorable when larger power-handling ability is required, and should see increased use as available power at shorter wavelengths grows. Increased power handling is also an advantage of a quasi-optical planar mixer [98], although the requirements in this area are less demanding at the present time.

G. Quasi-Optical Instruments

There may be no real distinction between components and instruments, but we use the latter term here for a device which makes a measurement in a largely self-contained manner. Quasi-optical instruments have been developed only relatively recently, as quasi-optical systems have become more common and the need for measurements on quasi-optical components has become evident. One very important function is the measurement of power flowing in a quasi-optical beam. Several designs using bolometers fabricated on very thin membranes combined with antenna structures have been developed [99], these are relatively insensitive to the angle of the incoming radiation and show little polarization dependence. A photoacoustic power meter has a relatively large (40 mm) aperture and measures the power absorbed by a thin film, using a microphone. Frequency dependence is minimized across the 300–1400 GHz range by using a Brewster angle input window [100]. The impedance of a quasi-optical component can be measured using a vector network analyzer [101]. While the system reported does not make extensive use of quasi-optical components, extension to higher frequencies would plausibly be effected entirely quasi-optically. Another function that is very effectively implemented using quasi-optical techniques is the measurement of noise on local oscillators at millimeter wavelengths. Several such systems have been developed utilizing the high Q provided by a quasi-optical cavity as a discriminator [102].

V. Quasi-Optical System Design and Examples

The very wide variety of quasi-optical systems and the functions they are used to perform make it difficult to define precisely a set of rules for system design. The following is intended as an introduction to this complex and interesting topic.

The starting point for system design is determination of the beam waist radii at critical points in the system. The most demanding components in this regard are usually interferometers used as frequency selective devices or diplexers. Avoiding loss due to either imperfect beam overlap or to beam growth imposes lower limits on the beam waist radius in the section of the Gaussian beam in which these components are located. Resonators must be coupled to a beam having the proper beam waist radius. The beam waist in an antenna feed system is generally defined by the antenna illumination desired and the focal ratio [103]. Power is generally to be coupled to a single-mode system as exemplified by those given in Table 2, each of which has a specified equivalent waist radius. The general goal of the system designer is then to use the Gaussian beam transformation formulas given by (20)–(22) to couple the beam waists without loss. This defines the set of lenses and/or mirrors which are placed between the various components.

A commonly encountered constraint is to minimize the number of focusing elements or to maximize the distance between focusing elements. If one has a pair of apertures

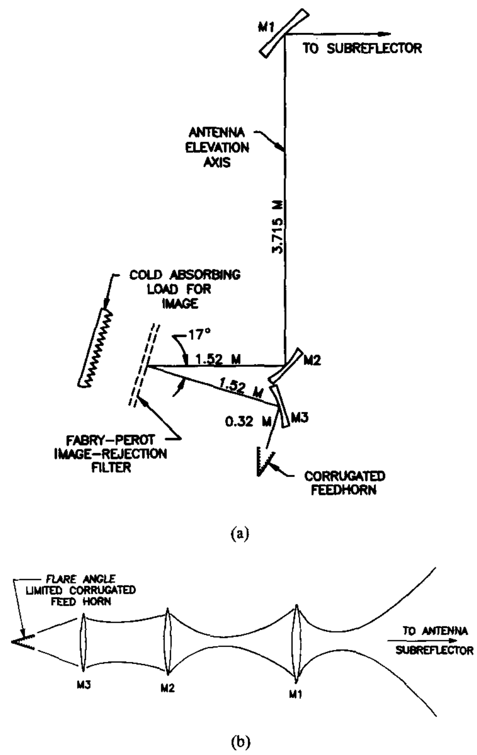

Fig. 8. (a) Quasioptical antenna feed system described in [104], which includes Fabry-Perot image-rejection filter and beam transport over elevation axis. (b) Unfolded schematic of the feed system showing focusing elements represented as thin lenses and Gaussian beam contours.

separated by distance $2D$ and the acceptable beam truncation level is specified, then we have effectively defined the maximum beam radius w at a distance D from the beam waist, which should be located symmetrically between the two apertures. With (7) or (9), we can solve for the value of the beam waist radius which *minimizes* the beam radius at a specified distance, or which *maximizes* D for a given value of w. The relationship found is $D = \pi w_o^2/\lambda$ or $w_o = [\lambda D/\pi]^{0.5}$, with $w = \sqrt{2} \cdot w_o$. The maximum separation of the apertures representing the finite-sized focusing elements is thus seen to be twice the confocal distance.

The design procedure described above refers to a single frequency. The challenge becomes greater if, as is often the case, the quasi-optical system is to work over a sufficiently wide bandwidth that the transformation equations and/or the desired waist radii vary appreciably. There is no guarantee that perfect coupling can be achieved over the specified range of frequencies, but the guidelines for frequency-independent beam transformation discussed in Section II can be quite helpful. A number of quasi-optical systems which make extensive use of quasi-optical techniques are described in [104]–[107].

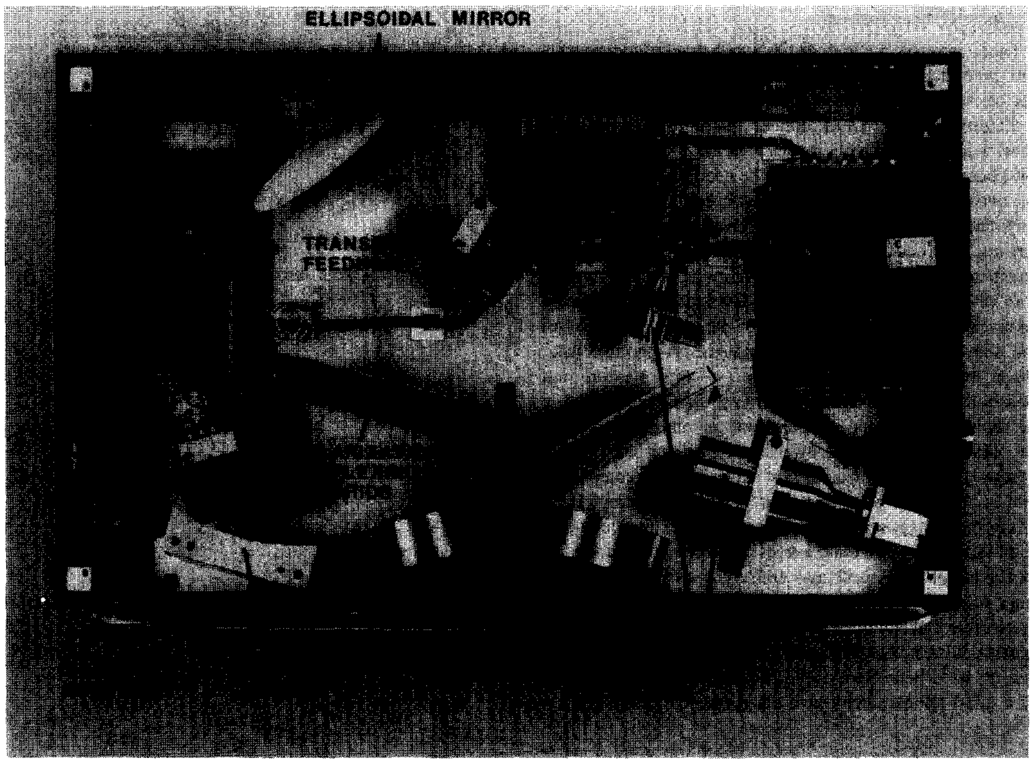

Fig. 9. Materials measurement system which simultaneously determines reflectivity of sample at frequencies of ≅ 45 and 90 GHz. The two beams are diplexed by wire grids, and final beam transformation is carried out by Teflon lenses which produce beam waists approximately 15 cm from the lower edge of the unit.

One area in which quasi-optical system design is widely applied is antenna feed system design. The basic requirements for analyzing and optimizing aperture and beam efficiencies for systems of fairly large f/D ratio such that the paraxial approximation is valid are given in [34], [71], and [103]; this fortunately includes almost all Cassegrain systems encountered in modern submillimeter- and millimeter-wavelength antennas. Quasi-optical antenna feeds at millimeter wavelengths include such functions as calibration, single sideband filtering, local oscillator injection, and polarization diplexing and processing [71], [105]. Specific frequency dependence (in particular, frequency independence) of antenna performance can be obtained [106]. Quasi-optical feed systems are closely related to beam waveguides used for beam transport in conjunction with large microwave antennas to permit transmitters and receivers to be kept at essentially fixed locations near the ground [108]. Quasi-optical antenna feed system design at relatively high frequencies differs from beam waveguide design primarily in that the much smaller wavelengths involved make it easier for focusing elements to be sufficiently large that loss due to truncation is negligible.

An interesting example of a millimeter quasi-optical antenna feed is a three-mirror system designed to transport the beam over the elevation axis of the antenna and provide single sideband filtering [107]. The system layout and the Gaussian beam equivalent using lenses to represent focusing elements are shown in Fig. 8. In this design, the Fabry–Perot filter used at nonnormal incidence determines the minimum beam waist radius in that section, but the overall system, which uses reflective optics exclusively, is designed to be relatively frequency-independent. An important application of quasi optics is to multiband receiver systems [109]. A quasi-optical antenna feed for a satellite earth-observing system which multiplexes ten channels between 118 GHz and 183 GHz into a single beam has been designed and fabricated [110]. In this system, dichroic plate filters are used to separate the different bands, and ring-type Fabry–Perot interferometers are used for local oscillator injection. The signal beam is transformed by off-axis ellipsoidal mirrors, while lenses are employed for the local oscillator, where loss is less critical.

Many systems for measurement of materials properties utilize resonators, as discussed above, but alternative quasi-optical approaches have been developed as well [111]. An example of a quasi-optical system used to measure the reflectivity of a variety of samples is shown in Fig. 9, which operates at two frequencies simultaneously utilizing orthogonal linear polarizations diplexed with a wire grid polarizer fabricated on a dielectric substrate. The beam transformation is carried out by a combination of lenses and mirrors. The system produces relatively small beam waists at the location of the sample, which is 15 cm from the edge of the system envelope. Efficient determination of materials properties even under rapidly varying conditions can be obtained by simultaneous dual-frequency measurements.

VI. Conclusions

We have reviewed the fundamentals both of quasi-optical fundamental-mode Gaussian beam propagation and of focusing elements used to control beam growth and produce beam waists required for specific components. Quasi-optical components have undergone a remarkable expansion during the past few years, and include a very wide variety of polarization processors, filters, diplexers, ferrites, and resonators which collectively can carry out almost all of the functions available in guided-wave transmission media. Considerable work remains to be done in terms of optimizing performance of mirrors and lenses, and analyzing complex systems with more than one mode. New quasi-optical components include power combiners, multipliers, and other devices with multiple active elements. In terms of applications, it is clear that quasi optics has a very promising future in the areas of materials measurement, astronomical and atmospheric remote sensing radiometers, and a wide variety of radar systems.

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In 1975 he moved to the University of Massachusetts, where he has developed instrumentation for the 14 m antenna and carried out astronomical observations. He initiated development of cryogenic mixer receivers at the Five College Radio Astronomy Observatory, developing a system with very low noise as well as exceptional calibration accuracy as a result of the extensive use of quasi-optical technology for single sideband filtering and input switching. This effort led to the development of the QUARRY focal plane array, a 15 element system for radio astronomical spectroscopy operating in the 3 mm wavelength region. In 1981 he led a team which carried out the first submillimeter astronomical observations with a laser local oscillator heterodyne system.

At the University of Massachusetts, Dr. Goldsmiths's astronomical research has addressed questions of the relationship of molecular clouds to young stars and detailed studies of molecular material near the center of the Milky Way. A professor at the University of Massachusetts since 1986, Dr. Goldsmith is one of the coinvestigators for the Submillimeter Wave Astronomy Satellite (SWAS). His reseach in technology has focused on Gaussian optics, quasi-optical system design, and imaging systems. In 1982 he was one of the founders of the Millitech Corporation, where he is Vice President for Research and Development and works primarily in the area of millimeter-wavelength imaging and quasi-optical component and system design. Dr. Goldsmith is a member of the American Astronomical Society, Sigma Xi, and URSI. He was named MTT-S Distinguished Lecturer for the period 1992–1993.