J. Indian Inst. Sci. 62 (A), Sept., 1980, Pp. 159–170.

Q-band beam waveguide

GLORY JOHN*
Electrical Communication Engineering Department, Indian Institute of Science, Bangalore 560 012.

Received on August 23, 1980.

Abstract

A report of the design, development and performance characteristics of a Q-band (8 mm) confocal, zoned, dielectric lens beam waveguide is presented.

Key words: Beam transmission, beam waveguide, millimeter wave transmission.

1. Introduction

The pioneering work of Goubau, followed by several other investigators[1–22] on beam waveguides using iris, confocal mirrors and lenses, and guides using gas focusing system, including the study of the presence of higher order modes and their effect on the transmission characteristics of beam modes, stability of modes, phenomenon of mode conversion due to misalignment of phase transformers and the problem of launching a Gaussian beam onto the beam waveguide, has led to the evolution of a new method of free-space guided wave long distance communication by millimeter, submillimeter and optical waves with very low dispersion loss, which is due to the utilisation of the principle of reiteration of wave beams at regular intervals.

The object of this work is to study the free space millimeter wave propagation characteristics for long distance communications and, as a first step, a 25-feet long guided wave test bench using dielectric zoned lenses has been designed and developed to work at 8 mm wavelength.

As far as can be gathered from available published literature, smooth surface lens has been used by the earlier investigators for the construction of beam waveguide. In order to reduce the (i) weight and (ii) absorption loss in the material, it has been thought worthwhile to use zoned dielectric lenses. It is also the object of this work to determine whether efficient reiteration of wave beams can be achieved at regular intervals by using zoned, instead of smooth, surface lens.

* Present address : Dept. of Mathematics, University of Dundee, Dundee DD1 4HN, UK.

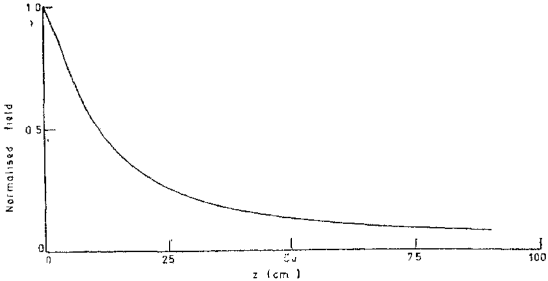

FIG. 1. Plot of axial field variation (theoretical).

The paper presents a report containing the design details of the beam waveguide and results of measurement of its performance characteristics.

2. Numerical computation of axial and radial fields

The mathematical formulation of the principle of propagation of waves guided by beam waveguides is based on electromagnetic wave beams of the type which exists in the Fresnel region of highly directional antennas and whose field distribution can be reconstituted at periodic intervals. Since the electromagnetic energy in the Fresnel region is essentially confined to a cylindrical space and the free space loss is insignificantly small, the reconstitution of the Fresnel character of the field by beam waveguide provides a method for long distance communication at millimeter wavelengths. The expression for the transverse electric field in terms of elementary waves[4] is

$$E(\rho, \phi, z) = \sum_{n=0}^{\infty} \sum_{m=-\infty}^{\infty} E_{mn}(\rho, \phi, z)$$

$$= e^{-jkz} \sum_{n=0}^{\infty} \sum_{m=-\infty}^{\infty} (-j)^m e^{jm\phi} \int_{\gamma=0}^{\infty} G_{mn}\left(\frac{\gamma}{\bar{\gamma}}\right) J_m(\gamma\rho) \times \exp\left(j \frac{\gamma^2}{2k} z\right) \gamma \, d\gamma \tag{1}$$

where $\bar{\gamma}$ is the mode parameter

$$G_{mn}(x) = x^m L_n^m(x^2) e^{-x^2/2} \tag{2}$$

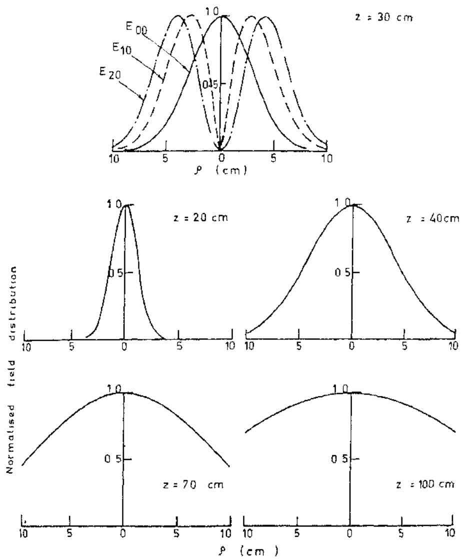

FIG. 2. Plot of radial field variation (theoretical).

are the Laguerre–Gaussian functions and

$$L_n^m (x^2) = \frac{e^x\, x^{-m}}{n!} \frac{d^n}{dx^n} [e^{-x}\, x^{n+m}] \tag{3}$$

are the generalised Laguerre polynomials.

The beam modes satisfy the following orthogonal relations

$$\int_{\phi=0}^{2\pi} \int_{\rho=0}^{\infty} E_{mn}\, E_{m'n'}\, \rho\, d\rho\, d\phi = \delta_{mn'}\, \delta_{nn'} \tag{4}$$

where

$$\delta_{mn} = \begin{cases} 0, & m \neq n \\ 1, & m = n. \end{cases} \tag{5}$$

The axial (z) field distributions for the fundamental mode E_{00} and the transverse (ρ) field distributions for E_{00} as well as some higher modes, computed using eqn. (1) with

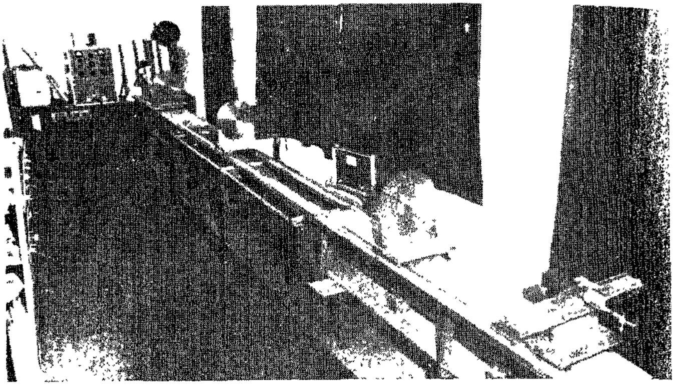

FIG. 3. Experimental set-up of the Q-band beam waveguide.

the help of DEC–10 computer are presented respectively in Figs. 1 and 2. These figures exhibit a decay of the E_{00} mode in the z-direction and a Gaussian form in its cross-sectional field distribution at different axial distances from the source. This is the desired property of a beam waveguide.

3. Experimental set-up

Figure 3 shows the experimental set up of the beam waveguide which has been designed and developed. It consists of uniformly spaced phase transformers (zoned dielectric lenses) which represent the actual guiding structure and terminations for launching and receiving the desired beam mode. The transmitting horn, which is a pyramidal horn with a gain of 22 *db*, is excited by a Reflex Klystron R5146. The receiving horn is similar to the transmitting horn, and the power output is taken through a bolometer to a power bridge.

4. Design of lens

4.1. *General*

The phase transformers are designed to advance the phase in the outer portion of the beam relative to the centre, according to the relation

$$\phi = \frac{k\rho^2}{D} \tag{6}$$

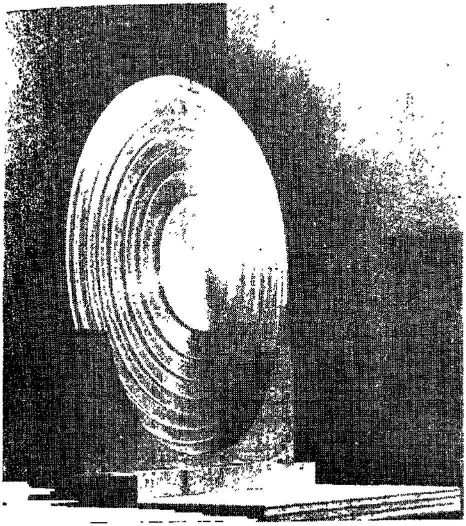

FIG. 4. Zoned dielectric lens $R = 15$ cm ; $f = 135$ cm.

where ϕ is the phase advance at a radius ρ, D is the spacing of the phase transformers and $k = 2\pi/\lambda$. The diffraction loss L_D of a phase transformer, caused by the cross-sectional limitation of the beam, is related to the maximum phase shift $\phi_{max} = kR^2/D$, where R is the radius of the phase transformer[5,10]. It has been shown by Christian and Goubau[5] that for the fundamental mode this loss drops below 0·01 db per iteration, if ϕ_{max} approaches 2π. Hence in the present work, the maximum phase shift for the fundamental mode has been fixed to a value of 2π, and, by fixing a suitable value for D, the aperture radius R has been determined. This value of R gives the minimum diffraction loss per iteration.

4.2. *Zoned dielectric lenses*

Simple hyperboloid contour dielectric lenses of large diameter are quite heavy, and have significant attenuation loss. These disadvantages can be reduced by employing the 'stepped' or 'zoned' construction. In a stepped lens, the maximum change in the optical path length which has to be introduced by the lens material is one wavelength. Hence the thickness of a planoconvex lens need never exceed $a = \lambda/(n - 1)$ (where λ is

Table I

Design dimensions of zoned lenses

Range of ρ (cm)	Thickness of lens (cm)
0 – 5·3	2·8
5·3 – 7·5	2·45
7·5 – 9·19	2·10
9·19–10·61	1·75
10·61–11·86	1·40
11·86–12·99	1·05
12·99–14·03	0·70
14·03–15·0	0·35

These values agree well with the actual path length calculations.

the wavelength and n is the refractive index of the material), irrespective of the aperture size. The zoned lenses of focal length $D/2$ have been constructed by machining annular steps of appropriate widths and depth into the surface of the dielectric sheet of refractive index n. The lenses were made in such a way that the phase change across the successive zones is 45° ($\pi/8$ radians), the depth of the steps being $d/8$. The theoretical efficiency of such a lens is very nearly equal to that of an ideal phase correcting lens[22].

Figure 4 shows the zoned, dielectric lens with a radius $R = 15$ cm and focal length $f(=D/2) = 135$ cm. Table I gives the design dimensions of the lenses used for the construction of the beam waveguide. The dielectric constant of the lens material is 2·56.

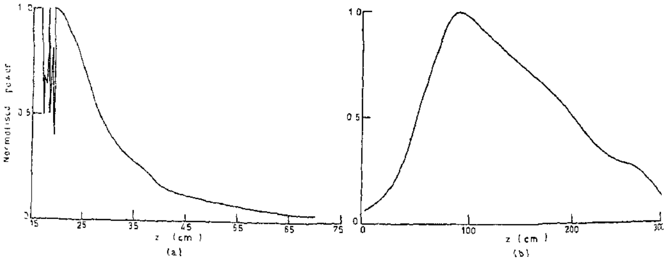

FIG. 5. Axial variation of the field: (*a*) without the lens (experimental); (*b*) with one lens (experimental).

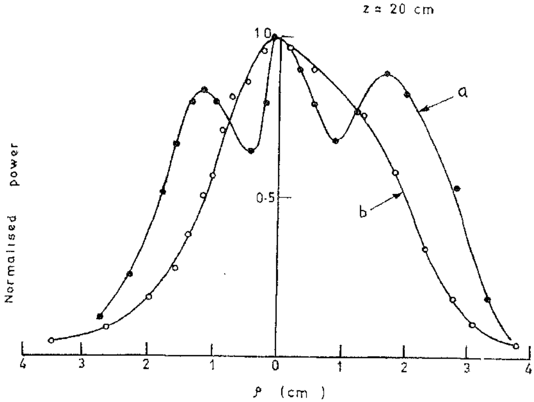

FIG. 6. Fundamental mode combined with the higher order modes (experimental).

5. Measurements

The results of measurements to explore the axial and cross-sectional field distributions with and without phase transformers are reported in Figs. 5–9. The normalised power patterns instead of field patterns are plotted. It is observed that:

(i) The axial field (the outer envelope of the field has been plotted for simplicity) is oscillatory very near the source (Fig. 5 *a*, without lens) and the oscillation persists for about 25 cm away from the source. The oscillation may be ascribed to the presence of higher order modes superposed on the fundamental mode.

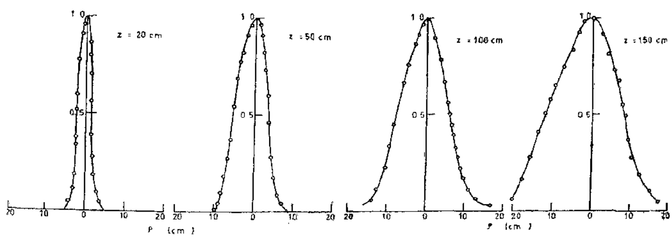

FIG. 7. Cross-sectional variation of the field without the lens (experimental).

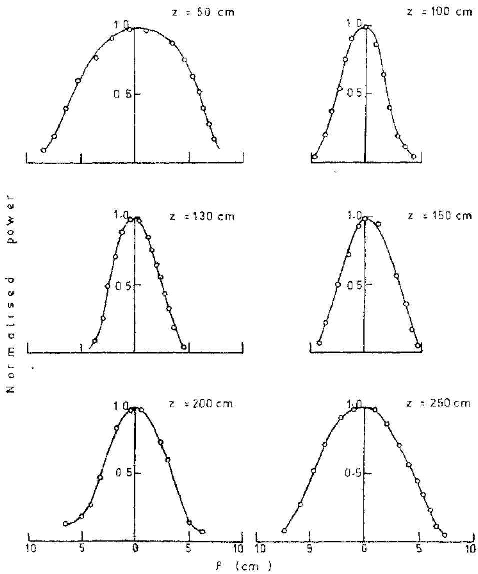

FIG. 8. Cross-sectional variation of the field with one lens (experimental).

(ii) The oscillation disappears after one lens is used (Fig. 5 *b*).

(iii) The higher order modes having higher rate of attenuation die out faster than the fundamental mode. This is evident from a comparison of the two figures in Fig. 6. which presents the cross-sectional field distributions very close to the source (Fig. 6 *a*) and 20 cm away (Fig. 6 *b*) from the previous location of the measurement.

(iv) The introduction of a phase transformer does not change the beam mode.

(v) The beam cross-section broadens considerably in the z-direction without any lens (Fig. 7).

(vi) With one lens, however, the beam undergoes a change from a broad to a narrow cross-section (near the focal point of the lens) and then the beam diverges, thus exhibiting the reiteration phenomenon.

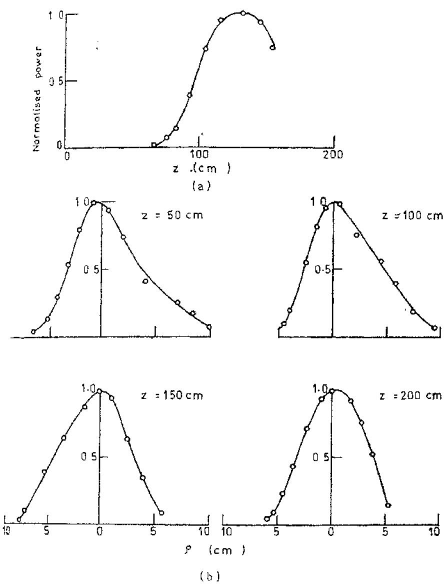

FIG. 9. Axial variation of the field : (*a*) with two lenses ; (*b*) Cross-sectional variation of the field with two lenses.

(vii) The effect of inserting the second lens on the axial and cross-sectional field distribution shows further the principle of reiteration (Fig. 9). The asymmetry (Fig. 9 *b*) is possibly due to slight tilt of the second lens with respect to the first lens.

6. Conclusions

It has been verified that (*a*) the wave beam is reiterated when confocal, zoned, dielectric lenses are used as phase transformers in place of smooth surfaced transformers in a beam waveguide, (*b*) properly aligned beam waveguide can be used for long distance communication at millimeter wave frequencies. Since the loss calculations and the calculations of constant energy flux contours have already been done for the beam waveguide by the earlier investigators[4], these have not been repeated for the case of zoned dielectric lenses.

Acknowledgement

The author gratefully acknowledges the help and encouragement received from Prof. (Mrs.) R. Chatterjee and Prof. S. K. Chatterjee for the above investigation.

References

1. Christian, J. R. and Goubau, G. — Measurements on an iris beam waveguide, *Proc. IRE*, 1961, 49, 1679–1680.
2. Fox, A. G. and Li, T. — Resonant modes in a maser interferometer, *Bell Syst. Tech. J.*, 1961, **40**, 453–488.
3. Degenford, J. E., Sirkis, M. D. and Steier, W. H. — The reflecting beam waveguide, *IEEE. Trans. on Micr. Th. Tech.*, 1964, *MTT*–**12**, 445–453.
4. Goubau, G. and Schwering, F. — On the guided propagation of electromagnetic wave beams, *IRE Trans. Ant. Prop.*, 1961, *AP*–9, 248–256.
5. Christian, J. R. and Goubau, G. — Experimental studies on a beam waveguide for millimeter waves, *IRE Trans. Ant. Prop.*, 1961, *AP*–**9**, 256–263.
6. Goubau, G. — Optical relations for coherent wave beams, *Symp. Electromagnetic theory and antennas*, *Copenhagen*, Pergamon Press, Oxford, 1962, 907–918.
7. Tien, P. K., Gordon, J. P. and Whinnery, J. R. — Focussing of a light beam of gaussian field distribution in continuous and periodic lens-like media, *Proc. IEEE*, 1965, **53**, 129–136.
8. Berreman, D. W. — A lens or light guide using convectively distorted thermal gradients in gases, *Bell. Syst. Tech. J.*, 1964, **43**, 1469–1475.
9. Schwering, F. — Reiterative wavebeams of rectangular symmetry, *Arch. der. Elek. Uber.*, 1961, **15**, 555–564.
10. Beyer, J. B. and Scheibe, E. H. — Higher modes in guided electromagnetic wavebeams, *IRE Trans. Ant. Prop.*, 1962, *AP*–*10*, 349–350.
11. Hirano, J. and Fakutsu, Y. — Stability of a light beam in a beam waveguide, *Proc. IEEE*, 1964, **52**, 1284–1292.
12. Eaglesfield, C. — Mode conversion loss in a sequential, confocal lens system, *Proc IEE*, 1964, **111**, 610–615.
13. Schwering, F. — On the theory of randomly misaligned beam waveguides, *IEEE Trans. Micr. Th. Tech.*, 1967, *MTT*–**15**, 206–215.
14. Goubau, G. and Christian, J. R. — Loss measurements with a beam waveguide for long distance transmission at optical frequencies, *Proc. IEEE*, 1964, **52**, 1739.
15. Scheibe, E. H. and Beyer, J. R. — Loss measurements of the beam waveguide, *IEEE Trans. Micr. Th. Tech.*, 1963, *MTT*–**11**, 18–22.
16. Christian, J. R., Goubau, G. and Mink, J. — Self-aligning optical beam waveguides, *IEEE Conf. Laser Engg. Applications*, Washington D.C., 1967.

17. GOUBAU, G. AND CHRISTIAN, J. R. — Some aspects of beam waveguides for long distance transmission at optical frequencies, *IEEE Trans. Micr. Th. Tech.*, 1964, *MT*-**12**, 212–220.

18. CHRISTIAN, J. R., GOUBAU, G. AND MINK, J. — Further investigations with an optical beam waveguide for long-distance transmission, *IEEE Trans. Micr. Th. Tech.*, 1967, *MTT*-**15**, 216–219.

19. BASKAKOV, S. E. — Excitation of beam waveguide, *Radio Engg. Electr. Phys.* (*USSR*), (Engl. Trans.), 1964, **9**, 492–499.

20. SCHWERING, F. AND ZARFLER, A. — Beam waveguide excitation by the aperture field of a tubular waveguide, *IEEE Trans. Micr. Th. Tech.*, 1967, *MTT*-**15**, 191–192.

21. CHAFFIN, R. J. AND BEYER, J. B. — A lowless launcher for beam waveguide, *IEEE Trans. Micr. Th. Tech.*, 1964, *MTT*-**12**, 555.

22. GARNHAM, R. H. — *Quasioptical components millimeter and submillimeter waves*, Ed. by F. A. Benson, Published by Life Books Ltd., London, 1969, 403–450.