quarter-guide wavelength, or odd multiples of this, away from the flange, causing the flange loss to be in quadrature with the theoretically calculable reflection coefficient, and so having a reduced effect on the magnitude of ρ_S.

References

[1] N. Marcuvitz, *Waveguide Handbook.* New York: McGraw-Hill, 1951, pp. 307–309.
[2] G. F. Engen, "An extension to the sliding short method of connector and adaptor evaluation," *J. Res. Nat. Bur. Stand.*, vol. 75C, nos. 3 and 4, pp. 177–183, July–Dec. 1971.
[3] G. Almassy, "A first-order correction to sliding short behaviour with application to the problem of measuring small losses," *IEEE Trans. Instrum. Meas.*, vol. IM-20, pp. 162–169, Aug. 1971.
[4] P. J. Skilton, "Loss, reflection and repeatability in waveguide flanged couplings," *Conf. Prc. Electromagnetic Meas., CPEM Dig.*, pp. 271–273, 1974.
[5] ——, "A technique for measuring the efficiency of waveguide-to-coaxial-line adaptor," *IEEE Trans. Instrum. Meas.*, vol. IM-27, pp. 231–234, Sept. 1978.
[6] D. L. Hollway and P. I. Somlo, "The reduction of errors in a precise microwave attenuator calibration system," *IEEE Trans. Instrum. Meas.*, vol. IM-22, pp. 268–270, Sept. 1973.
[7] P. I. Somlo, "The locating reflectometer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 105–112, Feb. 1972.

Dielectric Hemisphere-Loaded Scalar Horn as a Gaussian-Beam Launcher for Microwave Exposure Studies

PERAMBUR S. NEELAKANTASWAMY AND FOONG CHEE HONG

Abstract—A new type of Gaussian-beam launcher for producing a focused-microwave exposure field in biological experiments for selective partial-body irradiation is studied. The proposed launcher consists of a scalar horn (corrugated cylindrical open-ended waveguide) excited with a balanced hybrid (HE_{11}) mode and the aperture of the horn is loaded with a dielectric hemisphere. This launcher is similar to the structure described by one of the authors elsewhere [1], except that a dielectric hemisphere instead of a full sphere is used, with the result that the spherical aberration is considerably reduced, as well as that the weight and the size are, to a certain extent, reduced. It is shown that the present structure also produces in the image space of hemispherical lens, a near-circular Gaussian beam with a high-focusing factor. Design details, theoretical calculations, and experimental results concerning a practical *X*-band launcher are presented.

I. Introduction

In the recent past, Neelakantaswamy *et al.* [1]–[4] developed a class of microwave radiators termed as "Gaussian-beam launchers", to produce a focused exposure field in biological experiments for partial-body irradiations. These compact and simple structures with their ability to focus the microwave energy in a very small region indicate their practical utility, in the areas of biological researches and medical applications of microwaves, such as for selective heating of diseased/cancerous tissues. These launchers can also be used in noninvasive beam-wave reflectometric and spectrometric instrumentations for measuring complex permittivity of biological material at microwave frequencies, as indicated by Neelakantaswamy elsewhere [5]–[7].

When compared to the microwave beam-launching system described in [8], which consists of a plane-wave irradiated dielectric sphere (lens), the launcher formed by combining a scalar horn and a dielectric sphere [1] is a more practical source of microwave Gaussian beam. However, the use of a dielectric sphere as the focusing lens results in significant amount of spherical aberrations in the focal field, as indicated by Neelakantaswamy *et al.* in [9]. The aberration effects are mainly due to the path lengths of rays traversing the sphere (lens) and can be quantified in terms the spherical aberration function $K_0V(\sigma)$, defined in [10], [11].

In the present work, a Gaussian-beam launcher is formed by placing a dielectric hemisphere (instead of a full sphere) at the aperture end of corrugated circular waveguide (scalar horn). This enables a reduction in the path length of the ray in the lens-medium, and hence the spherical aberration effects are relatively minimized. Further, by using a hemisphere in the place of a full sphere, the launcher structure becomes less massive and smaller.

Manuscript received January 15, 1979; revised May 24, 1979.
The authors are with the Electronics Section, School of Applied Sciences, University Science Malaysia, Minden, Penang, Malaysia.

II. Description of the Proposed Structure

Fig. 1 illustrates the launcher structure presently proposed. It consists of an open-ended corrugated circular

0018-9480/79/0900-0797$00.75 ©1979 IEEE

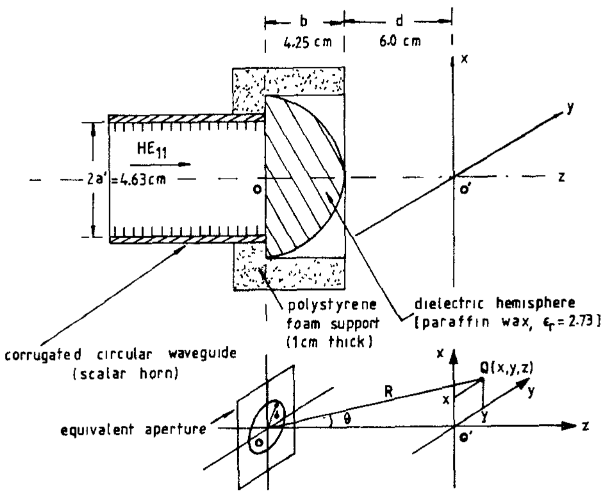

Fig. 1. The test Gaussian-beam launcher; corrugation parameters: Pipe inner diameter (2a′) = 46.30 mm; depth of corrugation = 8.45 mm; groove-width = 2.00 mm; tooth-width = 0.20 mm; corrugation density = 15 teeth per wavelength.

waveguide (scalar horn) which supports a balanced hybrid (HE_{11}) mode. Placed on this horn aperture is a dielectric hemisphere supported by a noninterfering polystyrene-foam holder.

Based on the analysis presented in [12], the resulting near-field distributions $U^Q_{\theta\phi}$ at the principal planes in the focal region of the hemispherical lens are given by

$$U^Q_{\theta\phi} = \frac{W^2}{\dfrac{K_0^2 W^2}{b^2} + j\beta} \exp\left[\frac{-K_0^2 \sin^2\theta}{\dfrac{K_0^2 W^2}{b^2} + j\beta}\right] \tag{1}$$

where

$$\beta = \frac{4K_0}{\sigma^2}\left[V(\sigma) + \frac{\sigma^2}{2z}\right]$$

$$W = 0.6437\, a'$$

$$K_0 = 2\pi/\lambda_0 \qquad (\lambda_0 = \text{free-space wavelength}).$$

Here the quantity β denotes the phase factor related to the spherical aberration function $K_0 V(\sigma)$ [10], [11]. The other quantities are illustrated in Fig. 1.

The structure depicted in Fig. 1 can be designed for specified constraints on its beam characteristics [13]. For example, if the desired beam-spot size at a distance of $z = d$ from the hemisphere is taken as $2\theta_c$ (in angular dimension θ_c represents the position of the first null), and if D is the edge taper of the horn expressed in decibels, then the required lens-radius (b) can be obtained approximately by solving the following transcendental equation [13]:

$$(\pi^2/4 + A^2)^{1/2} = 1.4715187\left(\frac{b}{W}\right)\sin\frac{\theta_c}{2}\exp\left[\frac{b^2 \sin^2\theta_c}{W^2}\right] \tag{2}$$

where $A = \cosh^{-1}(B)$, and the factor B is determined by a pair of parametric equations:

$$B = \frac{v\left(1 + \dfrac{C}{2}\right)}{2J_1(v) + 4C\dfrac{J_2(v)}{v}} \tag{3a}$$

$$C = (10^{D/20} - 1) = \frac{2J_1(v) - vJ_0(v)}{J_1(v) + \dfrac{4J_2(v)}{v} - J_3(v)} \tag{3b}$$

and

$$v = K_0 b \sin\theta.$$

Here J_0, J_1, J_2, and J_3 represent the ordinary Bessel functions of first kind and of order 0, 1, 2, and 3, respectively.

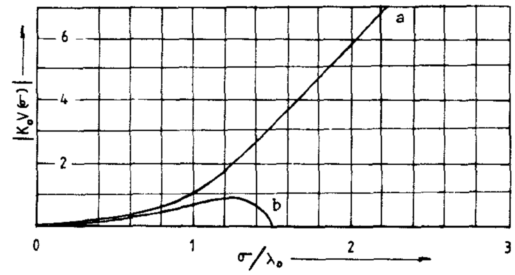

Fig. 2. Spherical aberration function versus normalized radius of the equivalent aperture (a) Full sphere. (b) Hemisphere.

III. Results and Discussions

An X-band test launcher of the dimensions shown in Fig. 1 was designed and fabricated. The corrugated pipe was designed, based on the theoretical results given in [14], for an aperture edge taper of $D = 25$ dB at a frequency of 9.5 GHz. The desired spot size at a distance of $z = d = 6$ cm along the optical axis from the lens is taken as $2\theta_c = 28°$. This corresponds to a spot-diameter of 5 cm at $z = d = 6$ cm. Hence the sphere radius is calculated to be nearly equal to $b = 4.25$ cm. The dielectric hemisphere was made with paraffin wax ($\epsilon_r = 2.73$) and was supported at the horn aperture by a polystyrene-foam support.

The spherical aberration function calculated for this lens, using the ray-tracing procedure given in [10], [11] is presented in Fig. 2 as a function of the equivalent aperture radius σ, normalized with respect to the free-space wavelength λ_0. For comparison, the aberration function resulting from the use of a full sphere is also shown in Fig. 2. A considerable reduction in the aberration effects when the dielectric hemisphere is used as the lens is evident from these results.

Near-field measurements were carried out at a frequency of 9.487 GHz and measured and calculated patterns at $d = 6$ cm of the test launcher are presented in Fig. 3. From the results given here, the following inferences can be made. 1) The present structure produces a near-circular Gaussian beam in the proximity of the focusing lens as was observed with the beam launcher of

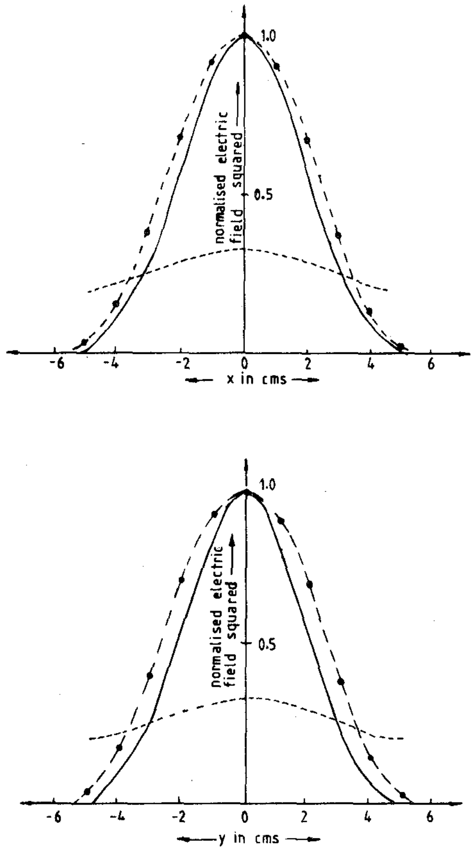

Fig. 3. Calculated and measured electric field squared at $d=6.0$ cm. (a) Along the direction of the incident electric field vector. (b) Along the direction of the incident magnetic field vector. —— theoretical; ●-●-●-● experimental; ------ experimental (without hemisphere lens).

[1]. 2) The use of a dielectric hemisphere as a lens reduces spherical aberration and also makes the structure relatively lighter and more compact. 3) A simple design procedure leads to the calculations of the launcher dimensions for prescribed constraints (say, the spot size) on the Gaussian beam.

References

[1] P. S. Neelakantaswamy, K. K. Gupta, and D. K. Banerjee, "A Gaussian-beam launcher for microwave exposure studies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 426–428, May 1977.

[2] ——, "A compact gaussian-beam launcher for microwave exposure studies at 2450 MHz," presented at the 1978 Symp. on Electromagnetic Fields in Biological Sys., Ottawa, Canada, June 1978.

[3] ——, "A compact light-weight Gaussian-beam launcher for microwave exposure studies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 665–666, Sept. 1978.

[4] ——, "A simple microwave gaussian-beam launcher for selective partial-body exposures in biological substances," presented at the 8th European Microwave Conf., Paris, France, Sept. 1978.

[5] P. S. Neelakantaswamy, "Noninvasive beam-wave reflectometric instrumentation for measuring complex permittivity of dielectric materials at microwave frequencies," *Rev. Sci. Instrum.*, vol. 49, pp. 858–860, June 1978.

[6] P. S. Neelakantaswamy, K. K. Gupta, and K. Basavaraju, "A non-invasive partial-body exposure method for measuring the complex permittivity of biological substances at microwave frequencies," *Med. and Bio. Eng. and Comput.*, vol. 16, pp. 419–424, July 1978.

[7] P. S. Neelakantaswamy and R. Govindarajan, "Non-invasive beam-wave spectrometric instrumentation for measuring dielectric constant at microwave frequencies," *Rev. Sci. Instrum.*, vol. 50, pp. 649–651, May 1979.

[8] H. S. Ho, G. J. Hager, and M. R. Foster, "Microwave irradiation design using dielectric lenses," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 1059–1061, Dec. 1975.

[9] P. S. Neelakantaswamy, D. K. Banerjee, and K. K. Gupta, "Field aberrations in the focal region of a microwave gaussian-beam launcher," *Arch. Elek. Ubertragung.*, vol. 32, pp. 85–87, Feb. 1978.

[10] P. S. Neelakantaswamy and D. K. Banerjee, "Radiation characteristics of a dielectric sphere-loaded corrugated pipe," *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 728–730, Sept. 1975.

[11] ——, "Dielectric spherical antenna excited by a cylindrical corrugated waveguide," presented at the 5th European Microwave Conf., Hamburg, Germany, Sept. 1975.

[12] P. S. Neelakantaswamy, D. K. Banerjee, and K. K. Gupta, "Near-field characteristics of a scalar horn-fed dielectric spherical radiator," *Arch. Elek. Ubertragung.*, vol. 31, pp. 173–175, Apr. 1977.

[13] P. S. Neelakantaswamy and F. C. Hong, "Design of a microwave Gaussian-beam launcher with prescribed constraints on its beam-characteristics," *Arch. Elek. Übertragung.*, vol. 33, pp. 174–177, Apr. 1979.

[14] C. M. Knop and H. S. Wiesenfarth, "On the radiation from an open-ended corrugated pipe carrying the HE_{11} mode," *IEEE Trans. Antennas Propagat.*, vol. AP-20, pp. 644–648, Sept. 1972.