References

[1] M. Sucher, "Measurement of Q," in *Handbook of Microwave Measurements*, vol. 2, M. Sucher and J. Fox, Ed. Brooklyn, NY: Polytechnic Press, 1963, ch. VIII, pp. 417–493.

[2] H. LeCaine, "The Q of a microwave cavity by comparison with a calibrated high frequency circuit," *Proc. IRE*, vol. 40, pp. 155–157, Feb. 1952.

[3] V. M. Vakhnin and T. F. Kolodina, "Setup for measuring attenuation of the H_{01} wave in short waveguide sections by use of the resonance cavity method," *Radiotechnik. Electronik.*, no. 12, pp. 1486–1491, 1956.

[4] I. Kneppo, L. Nagy, and M. Weis, "The resonator bridge method of the microwave loss tangent measurement," *Elektrotechnický časopis*, vol. 26, pp. 338–343, Apr. 1975.

A Gaussian-Beam Launcher for Microwave Exposure Studies

PERAMBUR S. NEELAKANTASWAMY, KRISHNA KUMAR GUPTA AND D. K. BANERJEE

***Abstract*—A practical method of producing a focused-microwave exposure field in biological experiments, for selective partial-body irradiation, is described. The proposed structure consists of a dielectric sphere placed in front of, but displaced from, the open end of a corrugated pipe with quarter-wave teeth, carrying the HE_{11} mode. It is shown that this launcher produces a near-circular Gaussian beam in the proximity of the dielectric sphere, with a high on-axis gain factor. Theoretical expressions are derived for the EM fields of the focused beam-wave, and experimental results obtained from a practical launcher confirm the theoretical calculations made.**

Introduction

In the areas of biological researches and medical applications of microwaves, it may be desirable to focus microwave energy in a very small region, close to the focusing lens, for localized exposure of biological subjects. For example, a noncontact selective heating of diseased tissues as an alternative to surgical removal and for selective heating of wounded tissues in conjunction with chemotherapy, need a practical method of launching of a microwave Gaussian beam.

Recently, the theoretical calculations and electric-field measurements made by Ho *et al.* [1] to investigate the focusing effects of plane-wave irradiated dielectric spheres (lenses) of different diameters and dielectric properties indicated the possibility of obtaining a focused spot close to the dielectric sphere. However, the experimental arrangement described in [1], requires a plane-wave source, and hence an anechoic chamber as well as a high-power microwave generator. Hence, to increase the practical utility of the dielectric sphere for microwave irradiation, it is necessary to replace the incident plane wave with a more practical source.

A method of getting a focused microwave beam by means of a launcher (Fig. 1) consisting of a homogeneous dielectric sphere illuminated by a corrugated cylindrical waveguide aperture (scalar horn) is described. The corrugated pipe has quarter-wave teeth and carries the hybrid (HE_{11}) mode. The field distribution at the aperture of the corrugated pipe is used as the sphere-illuminating source and the dielectric sphere is placed in front of, but displaced from, this aperture. The waveguide-to-sphere offset can be chosen to be the optimum value for which the input VSWR is a minimum [2], [3]. The corrugated pipe and the offset dielectric sphere can be conveniently supported by means of a noninterfering, polystyrene-foam holder, as illustrated in Fig. 1. The purpose of the present work is to demonstrate the feasibility of obtaining a Gaussian (focused) beam in the proximity of the dielectric sphere with the system just described; and the results concerning the on-axis gain factor, etc., of the present launcher are compared with those of the system due to Ho *et al.* [1].

Manuscript received August 20, 1976; revised November 12, 1976.

P. S. Neelakantaswamy and D. K. Banerjee are with the Department of Electrical Engineering, Indian Institute of Technology, Madras, India.

K. K. Gupta is with the Center for Systems and Devices, Indian Institute of Technology, Madras, India.

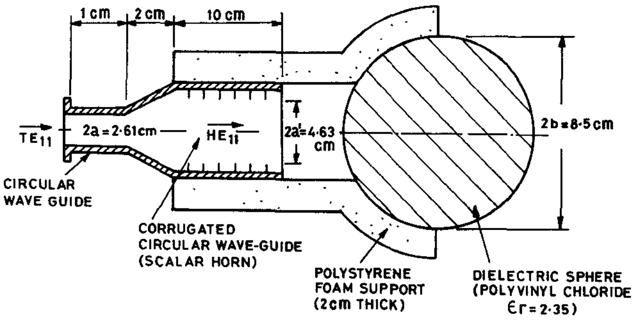

Fig. 1. The test Gaussian-beam launcher. Corrugation parameters: Pipe inner diameter ($2a'$) = 46.3 mm; depth of corrugation (l) = 8.45 mm; groove width (g) = 2.0 mm; tooth width (t) = 0.2 mm (thin blades); and corrugation density equals 15 teeth per wavelength (approx.)

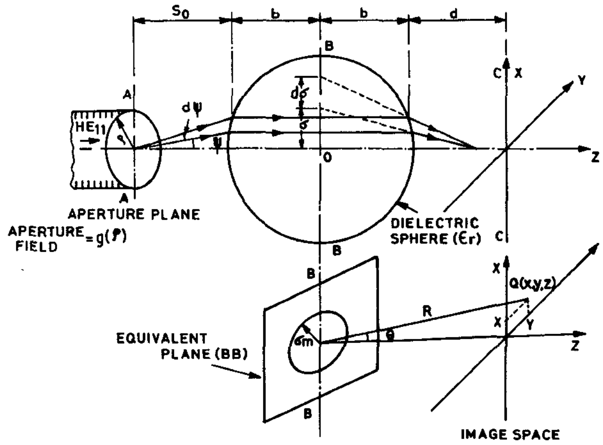

Fig. 2. Optical system showing the merdional section of the dielectric sphere. AA: Aperture plane of corrugated pipe with a symmetrical-field distribution $g(\rho)$, which illuminates the sphere. BB: Equivalent plane through the center of spherical lens with circular aperture of radius σ_m. CC: An XY plane at a distance d behind the dielectric sphere.

Theoretical Formulation

In [2] and [3], Neelakantaswamy and Banerjee presented a theoretical method to study the radiation behavior of a dielectric sphere kept offset in front of a waveguide aperture. This method is currently extended to analyze the beam wave behind the dielectric sphere of the arrangement depicted in Fig. 1. Referring to the optical system shown in Fig. 2, the approximate diffracted vertical- and horizontal-field components behind the sphere may be denoted as $U_\theta(\theta,R)$ and $U_\phi(\theta,R)$, respectively. The explicit expressions for these functions are given by [2, eqs. (1)–(4)] with the aberration function $V(\sigma)$ being replaced by $V'(\sigma)$, where $V'(\sigma)$ is given by

$$V'(\sigma) = V(\sigma) + \frac{b^2\sigma^2}{2z}. \tag{1}$$

Considering the field distribution at the aperture of the corrugated pipe (AA) carrying the hybrid HE_{11} mode, it is well known that [4]

$$g(\rho) = E_0 J_0(\alpha\rho) \tag{2}$$

TABLE I

Sphere diameter cm	Plane wave illumination of the spherical lens: Results due to Ho et al [1], Frequency = 10GHz — Polethylene sphere $\varepsilon_r = 2.26$, d = 6 cm, Focusing Factor: Ratio	dB	Polyfoam sphere $\varepsilon_r = 1.89$, d = 6 cm, Focusing Factor: Ratio	dB	Spherical lens illuminated by a scalar horn (Fig.1), Frequency = 10 GHz, s_0 = 3 cm — On-axis gain factor, relative to an istropic radiator: Ratio	dB
5.1	1.2	0.792	3.1	4.914	22.8	13.6
10.2	3.2	5.051	3.1	4.914	29.6	14.7
15.2	6.3	7.994	12.7	11.038	34.6	15.4
20.3	16.5	12.175	40.1	16.021	46.0	16.6
25.4	37.7	15.763	72.2	18.529	50.0	17.0
30.5	65.8	18.182	103.4	20.145	59.0	17.7
35.6	103.5	20.149	147.6	21.691	67.0	18.3
40.6	156.5	21.945	172.7	23.730	70.0	18.5

Note: The above results are based on equation (6) omitting the phase term β. That is, an aberration-free system is presumed. For $1 \leq \varepsilon_r \leq 4$, the paraxial focus lies outside the sphere. For large spheres, the gain factors will be lesser than the values given here, due to spherical aberration.

where $\alpha = 2.4048a'$. For a beam efficiency of 98.08 percent, $g(\rho)$ can be written as [5]

$$g(\rho) \simeq E_0 \exp(-\rho^2/W^2) \tag{3}$$

where $W = 0.6437a'$. Hence the power patterns $P_\theta(\psi)$ and $P_\phi(\psi)$ in the two principal planes at AA are given by

$$P_\theta(\psi) \text{ or } P_\phi(\psi) = |E_0 F(\psi)|^2 \quad \text{(symmetrical)} \tag{4}$$

where

$$F(\psi) = \frac{W^2}{2} \exp\left[\frac{-k_0{}^2 W^2 \sin^2 \psi}{4}\right].$$

Substituting the previous expression for $P_\theta(\psi)$ and/or $P_\phi(\psi)$ in [2, eqs. (3) and (4)], the amplitude functions $U_i{}^\theta$ and $U_i{}^\phi$ at the equivalent circular aperture BB can be evaluated. Further, by calculating the path difference between the actual and the ideal (aberration-free) path lengths traced by an arbitrary ray across the sphere, the aberration function $k_0 V(\sigma)$ can be determined, as described in [2]. Using these results, the diffracted-field components $U_\theta(\theta,R)$ and $U_\phi(\theta,R)$ can be numerically evaluated. However, closed-form expressions for these field components at any plane CC, which is at a distance d behind the sphere, can be written as

$$U_Q(x) = \frac{E_0 W^2}{\dfrac{k_0{}^2 W^2}{(s_0+b)^2} + j\,\beta(x)} \cdot \exp\left[-\frac{k_0{}^2}{\dfrac{k_0{}^2 W^2}{(s_0+b)^2} + j\,\beta(x)} \cdot \frac{x^2}{(d+b)^2 + x^2}\right]$$

$$U_Q(y) = \frac{E_0 W^2}{\dfrac{k_0{}^2 W^2}{(s_0+b)^2} + j\,\beta(y)} \cdot \exp\left[-\frac{k_0{}^2}{\dfrac{k_0{}^2 W^2}{(s_0+b)^2} + j\,\beta(y)} \cdot \frac{y^2}{(d+b)^2 + y^2}\right]. \tag{5}$$

Here the function β denotes a phase factor which implicitly includes the aberration involved. It is approximately given by

$$\beta = 4k_0 V'(\sigma)/\sigma^2. \tag{6}$$

The diffracted-field components given by (5) indicate that the beamwave behind the sphere is Gaussian. The characteristics of this beamwave are discussed below.

Results and Discussion

A test launcher of the dimensions shown in Fig. 1 was fabricated and near-field measurements were carried out at a frequency of 9.654 GHz with a dielectric sphere having a relative permittivity of $\varepsilon_r = 2.35$ (polyvinyl chloride) and of diameter equal to 8.5 cm. The optimum sphere offset $s_0 = 2.25$ cm was determined experimentally for minimum input VSWR performance, as indicated in [2], [3]. The near-field measurements were conducted using a dipole probe mounted on a nonreflecting support, by the method and with the precautions given in [6].

The measured and calculated patterns at $d = 6$ cm of the test launcher are presented in Fig. 3. From the results presented here, the following inferences can be made. 1) When the dielectric sphere is illuminated by a symmetrical field distribution from an aperture of a scalar horn, the resulting image field is a near-circular Gaussian beam; whereas, in the case of plane-wave irradiation, the resulting beam has elliptical cross section, with the major axis parallel to the direction of the incident electric field [1]. 2) Table I provides results on the focusing factors of dielectric spherical-lens systems with plane-wave illumination [1] and on the gain factors with an illumination by a scalar horn (present method). The large values of on-axis gain factors obtainable with small sphere radii is due to the scalar horn which illuminates the dielectric lens with a narrow, symmetrical, endfire pattern. Despite that, the gain factor increases with the increase in sphere diameter, the choice of a large sphere diameter is discouraged, as it would enhance the spherical aberration, resulting in significant defocusing errors.

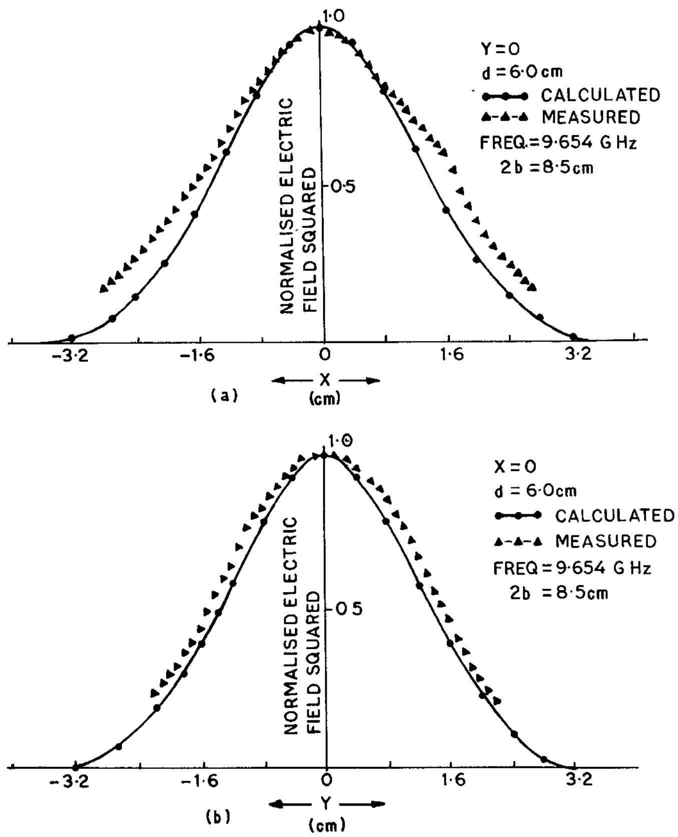

Fig. 3. Comparison of calculated and measured normalized electric field squared in a XY plane, 6 cm behind the dielectric sphere of the test launcher. (a) Along the direction of the incident electric-field vector. (b) Along the direction of the incident magnetic-field vector.

However, the enhancement of the focusing factor for a given sphere diameter to wavelength ratio can be achieved by decreasing the edge taper of the field distribution at the aperture of the scalar horn. A method to control this edge taper by means of changing the scalar-horn dimensions has been discussed in [7]. 3) Lastly, the effect of the dielectric constant of the sphere on the performance of the launcher can be considered. For the system shown in Fig. 1, the paraxial focal length is given by [8]

$$f_L = \frac{b}{2}\frac{\sqrt{\varepsilon_r}}{\sqrt{\varepsilon_r} - 1}. \tag{7}$$

Therefore, for the value of ε_r in the range of from 1 to 4, the focal point where the maximum intensity occurs will always lie outside the sphere. As against this, the selection of sphere diameter is rather critical with the plane-wave irradiation, in order to get the focal point outside the sphere [1].

In the present method, to obtain the focal length as given by (7), the sphere-illuminating aperture should be kept offset at a distance given by

$$s_0 = (f_L - b). \tag{8}$$

However, s_0 is usually selected on the basis of minimum input VSWR, as indicated before [2], [3]. Hence the resulting non-coincidence of the selected value for s_0, with the value given by $(f_L - b)$, causes a defocusing error and axially displaces the focal point in the image zone. But for a given launcher, a compromise between the minimum input VSWR and the defocusing error can be arrived at to get an optimum value for s_0.

Thus the present investigation indicates that by proper choice of the sphere diameter to wavelength ratio and the scalar horn dimensions, a specified Gaussian beam can be produced for localized exposure of biological subjects. A suitable dielectric material can be selected (with $1 \leq \varepsilon_r \leq 4$) for the spherical lens, so that the focal point is at a convenient location outside the sphere. The polystyrene-foam support ($\varepsilon_r \simeq 1$), which holds the sphere in front of the scalar horn, does not interfere with the launcher performances to a significant extent.

Research efforts are being made to improve the focusing action of the present setup by partially covering the sphere with a metallic surface [9] and/or by providing a sphere-to-air dielectric matching [10]. Furthermore, a detailed theoretical study is being carried out to analyze the beam wave behind the lens, taking into account the perturbing effects of the biological test object.

References

[1] H. S. Ho, G. J. Hagan, and M. R. Foster, "Microwave irradiation design using dielectric lenses," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 1058–1061, Dec. 1975.

[2] 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.

[3] ——, "Waveguide-fed dielectric spherical antennas," *Electron. Lett.*, vol. 10, pp. 540–541, Dec. 1974.

[4] C. Aubry and D. Bitter, "Radiation pattern of a corrugated conical horn in terms of Laguerre-Gaussian functions," *Electron. Lett.*, vol. 11, pp 154–156. Apr. 1975.

[5] C. Dragone, "An improved antenna for microwave radio systems consisting of two cylindrical reflectors and a corrugated horn," *Bell Syst. Tech. J.*, pp. 1351–1377, 1974.

[6] K. P. Dombek, "Über den Naherungscharakter Kirchhoffschev Randwerte für Nahfeldberechnungen," *Nachrichtentechn.Z.*, vol. 26, pp. 165–170, 1973.

[7] C. M. Knop and H. J. 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.

[8] G. Bekefi and G. W. Farnell, "A homogeneous dielectric sphere as a microwave lens," *Can. J. Phys.*, vol. 34, pp. 790–803, 1956.

[9] P. S. Neelakantaswamy and D. K. Banerjee, "Radiation characteristics of a waveguide excited dielectric sphere backed by a metallic hemisphere," *IEEE Trans. Antennas Propagat.*, vol. AP-21, pp. 384–385, May 1973.

[10] ——, "Radiation characteristics of a waveguide-excited spherical dielectric spheres with matched sphere/air boundary," *Electron. Lett.*, vol. 9, pp. 40–41, Jan. 1973.

A Microwave Irradiation Chamber for Scientific Studies on Agricultural Products

R. G. OLSEN, MEMBER, IEEE, G. A. GEITHMAN, AND D. H. SCHRADER, MEMBER, IEEE

***Abstract*—The design and testing of a chamber for uniform heating of objects with an intense microwave field is described. Methods for direct and inferred measurement of temperature in the microwave field during irradiation are discussed. A theoretical analysis was made to determine the range of electrical parameters for which heating will be uniform. This analysis was verified experimentally. Curves for determining the rate of energy absorption in cylindrical posts are given for a wide range of electrical parameters.**

Introduction

In recent years there have been many attempts to quantify the causal relations between the effects of high-intensity microwave irradiation and various measures of the radiation dosage. Effects have been reportedly correlated with the following quantities:

Manuscript received February 26, 1976; revised November 8, 1976. This work was supported by the National Science Foundation under Grant GK-40238.

R. G. Olsen and D. H. Schrader are with the Department of Electrical Engineering, Washington State University, Pullman, WA 99163.

G. A. Geithman was with the Department of Electrical Engineering, Washington State University, Pullman, WA 99163. He is now with the Boeing Aerospace Company, Kent, WA 98031.