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Open-Ended Circular Waveguide with a Curved Corrugated Disk at its Aperture as a Diathermy Applicator

PERAMBUR S. NEELAKANTASWAMY AND ARTHUR RAJARATNAM

***Abstract*—A direct-contact type of diathermy applicator consisting of an open-ended circular waveguide loaded with a curved (concave) corrugated disk at its aperture is described. The waveguide is dimensioned to support the dominant TE_{11} mode. Performance characteristics of this applicator are compared with those of an identical structure having a flat corrugated disk at the aperture rim [1]. Also, the superiority of the proposed applicator in respect of improved beam symmetry and reduced edge-diffraction effect (leakage) is indicated. Experimental results on the near-field distributions in the principal planes of a test applicator are presented and are compared with relevant results obtained from a flat-disk loaded applicator [1] of identical dimensions. Also, to get improved input VSWR performance (VSWR less than 1.6), off-setting the corrugated disk (flat or curved) behind the aperture is suggested and is also demonstrated experimentally. Furthermore, as a design flexibility and to simplify fabrication, filling the corrugation grooves with a suitable dielectric material is suggested and explained. Lastly, the feasibility of using a simple corrugated circular waveguide as an alternative direct-contact type of applicator is discussed.**

I. Introduction

Stuchly *et al.* [1] presented a design method and experimental results for a direct-contact circular-aperture diathermy applicator consisting of an open-ended circular waveguide flanged with a flat corrugated disk at its open end [1, fig. 2]; and they effectively demonstrated its acceptable performance in respect to uniform heating patterns, low power leakage, good beam symmetry, compactness of the structure, and low input VSWR at X- and S-band frequencies.

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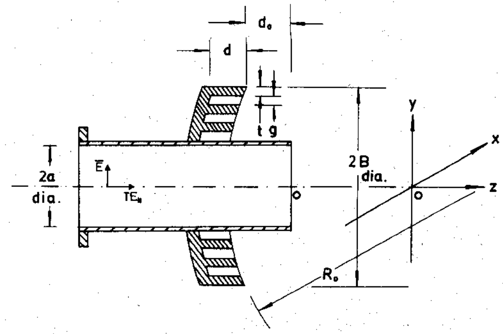

Fig. 1. Direct-contact applicator formed by a circular waveguide with a curved (concave) corrugated flange kept off-set behind the waveguide aperture. Frequency 9.47 GHz. Dimensional details: $2a = 25$ mm; $t = 2.0$ mm; $g = 2.0$ mm; $2B = 53$ mm; $R_0 = 150$ mm; Depth of corrugations d: 8.2 mm without dielectric and 4.9 mm with dielectric. (Dielectric used: Paraffin wax, $\epsilon_r = 2.73$). Off-set distance d_o is adjustable for minimum input VSWR.

The structure described in [1] is well known in antenna engineering as a primary feed with the designation "corrugated conical horn with 90° flare angle" [2],[3]. These radiators, in general, exhibit a good beam symmetry and low edge leakage (that is, side-lobe power) by virtue of quarter-wave choke action caused by the grooves of the corrugations [3]. However, the full benefits of these structures are realized only if the diameter $2B$ of the corrugated disk is much larger than the wavelength λ [4]. Otherwise, a disk of small diameter having a few corrugations would not suppress the edge fields effectively, with the result that edge-diffracted secondary field components may still be present, causing asymmetry in the main lobe with a distorted E-plane pattern and power leakage through side lobes in the forward and back regions of the aperture plane [5].

When this type of radiator is used as direct-contact diathermy applicators as suggested in [1], the diameter of the corrugated disk should be kept small in order to make the unit compact and light weighted; hence, only a few (2 to 4) corrugations on the disk is desirable. It means, therefore, that only a partial suppression of edge field could be realized.

In the present work, a modification to the applicator of [1] is suggested so as to realize almost a complete suppression of edge effects in spite of the diameter of the corrugated disk being small. The proposed modification is to replace the flat corrugated disk at the waveguide aperture by a curved (concave) one [6]–[9], as illustrated in Fig. 1. Relevant improvements in the performance characteristics of this modified structure are studied here in detail.

II. Description of the Proposed Structure and Design Considerations

Referring to Fig. 1, an open-ended circular waveguide is loaded with a curved corrugated disk at its aperture end. The inner diameter of the circular waveguide $2a$ is such that, the dominant (TE_{11}) mode at the working frequency alone propagates in it. The groove depth d of corrugations is made to be greater than a quarter of the wavelength λ so that surface waves are eliminated. The groove width g and the tooth width t of the corrugations are dimensioned to get a fairly large corrugation density (that is, a number of corrugations per wavelength). The diameter of the corrugated disk $2B$ is made to be less than twice the wavelength so the structure is compact enough to be used as a direct-contact applicator. In Fig. 1, the disk consists of three corrugations.

The radius of curvature R_0 of the corrugated disk is chosen to be approximately five times the wavelength, which ensures no

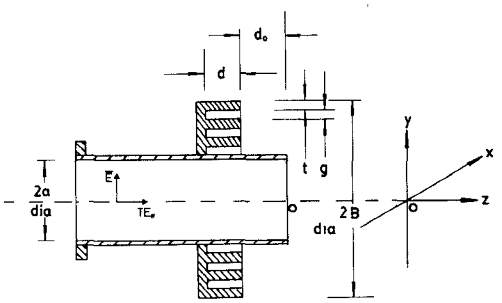

Fig. 2 Direct-contact applicator formed by a circular waveguide with a flat corrugated flange kept off-set behind the waveguide aperture (Details as in Fig. 1).

adverse fabricational problems. The dimensional details of an X-band applicator are furnished in Fig. 1. Also, an identical structure with a flat disk is depicted in Fig. 2 with relevant dimensional details. Both the structures (of Figs. 1 and 2) are excited in the TE_{11} mode by means of a rectangular-to-circular waveguide transition. (However, a coaxial-type coupling can also be used, as suggested in [1].)

It has been demonstrated by one of the authors elsewhere [6]–[9] that the curved corrugated disk of the radiator shown in Fig. 1 can tilt the wavefronts in the corrugated region towards the beam axis and thereby reduce the intensity of edge diffractions at the disk rim. This, in turn, would improve the beam symmetry and reduce the leakage since the edge-diffracted secondary fields are minimized.

When the radiating structures depicted in Figs. 1 and 2 are used as direct-contact applicators, the circular waveguide of these units, which opens onto a corrugated flange (flat or curved), comes in contact with a multilayered dielectric medium formed by successive layers of skin, fat, and subcutaneous tissue of the test subject. The input admittance of the circular waveguide, therefore, becomes a complex function of the external, stratified, and planar layers of the biomedia [10],[11]; hence, for effective coupling of the microwave power to the surface under irradiation, the input VSWR of the applicator must be adjusted for a value close to unity, to ensure matching and maximum power transfer. Presently, a technique, described in [3], is recommended for this purpose. This method involves off setting the corrugated flange (flat or curved) behind the aperture as illustrated in Figs. 1 and 2. Depending on the characteristics of the biomedium which loads the applicator and the frequency of operation, the off-set distance (d_0) can be adjusted for a minimum value of the input VSWR.

In fabricating a curved corrugated disk of the structure depicted in Fig. 1, it may be difficult to machine the flange to get corrugations of depth d greater than a quarter of the wavelength λ due to the curvature involved. To overcome this problem, one can use shallow-grooved corrugations, filled with a suitable dielectric (of relative permittivity $= \epsilon_r$) with the condition that

$$d > \frac{1}{\sqrt{\epsilon_r}} \frac{\lambda}{4}. \tag{1}$$

By this technique, the depth of corrugations d required to be machined is reduced considerably, and, therefore, the fabrication becomes simpler. This method is also suitable for the flat-disk type of applicators discussed in [1].

III. Experimental Results and Discussion

Test applicators shown in Figs. 1 and 2 operating in the X-band frequency range were designed and fabricated. Near-field measurements close to the aperture were carried out at a frequency of 9.47 GHz. Measured patterns at a distance of 2.0 mm from the waveguide aperture plane are presented in Fig. 3. From these results the following inferences can be made. 1) Half-power beam widths of the patterns of the flat-disk loaded applicator (Fig. 2) along the x and y directions are 17 mm and 18 mm, respectively. The corresponding values for the curved-disk loaded applicator (Fig. 1) are 16.8 mm and 17.2 mm. Hence, the beam-width ratios for these applicators are 94.5 percent and 97.6 percent, respectively. This indicates that a better symmetric pattern can be realized with the applicator of Fig. 1 in comparison with that of Fig. 2. 2) In the E-plane pattern (that is, along the y-direction) of the curved-disk loaded applicator, the first minor lobe level is lower (by about 5 dB) than that of the flat-disk loaded version.

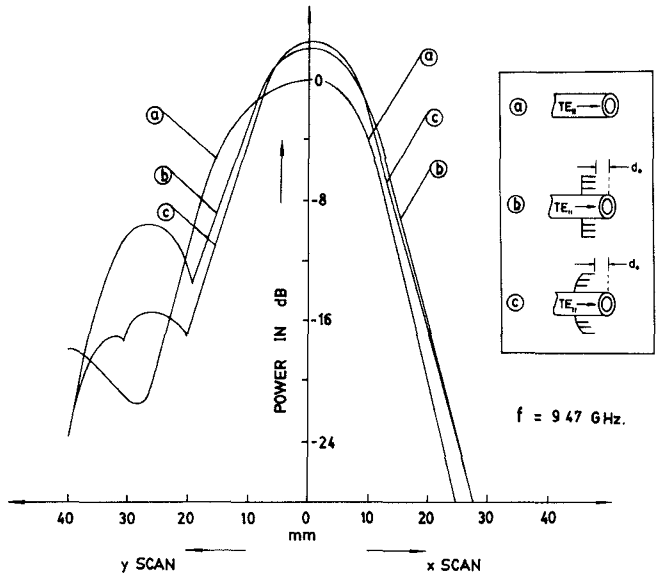

Fig. 3 Near-field patterns of the test applicators measured at $z = 2$ mm from the waveguide aperture, using corrugated disks without dielectric filling. For flat disk loading, disk off-set distance d_o for minimum input VSWR of $1.4 \simeq 7$ mm For curved disk loading, disk off-set d_o for minimum input VSWR $1.5 \simeq 5$ mm.

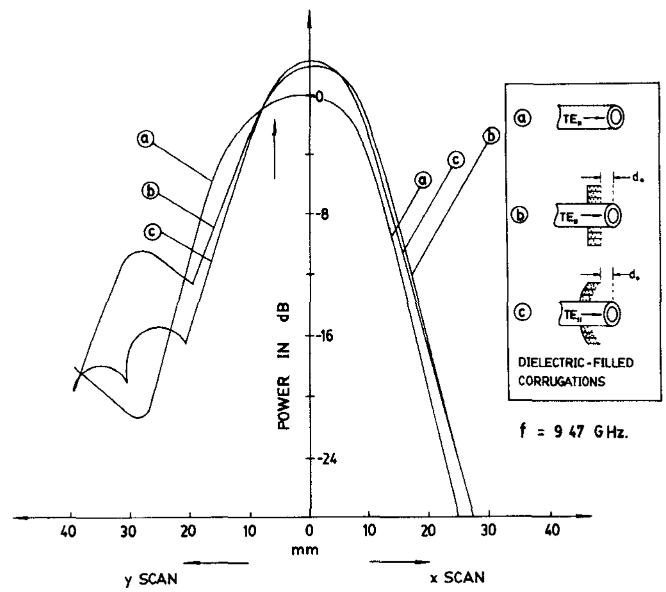

Fig. 4 Near-field patterns of the test applicators measured at $z = 2$ mm from the waveguide aperture using corrugated disks with dielectric (paraffin wax) filling in the grooves a. Open-ended circular waveguide. b. Test applicator of Fig. 2 with disk off-set d_o of 8 mm to give minimum input VSWR of 1.6. c. Test applicator of Fig. 1 with disk off-set d_o of 10 mm to give minimum input VSWR of 1.5.

TABLE I
MEASURED VALUES OF THE INPUT VSWR OF TEST APPLICATORS

Serial No	Test Applicator	Load *In Vivo*: Medial Palmar space Subject: Male Age: 37 yrs.	Load *In Vivo*: Upper outer quadrant of the left breast. Subject: Male; Age: 37 yrs.	Load *In Vivo*: Cheek-portion directly upon the zygomatic bone. Subject: Male: 37 yrs.	Remarks
		Measured input VSWR: (Mean value ± Std. Deviation) & Disk off-set distance d_o in mm			
1	Applicator of Fig. 1	2.10 ± 0.07, $d_o = 0$ 1.45 ± 0.03, $d_o = 4.5$	1.90 ± 0.05, $d_o = 0$ 1.50 ± 0.04, $d_o = 5.2$	2.20 ± 0.03, $d_o = 0$ 1.60 ± 0.10, $d_o = 6.0$	1. Frequency of operation: 9.47 GHZ
2	Applicator of Fig. 1 with shallow grooves filled with dielectric	1.80 ± 0.08, $d_o = 0$ 1.30 ± 0.10, $d_o = 7$	1.70 ± 0.07, $d_o = 0$ 1.50 ± 0.07, $d_o = 6$	1.90 ± 0.20, $d_o = 0$ 1.60 ± 0.04, $d_o = 5.3$	2. Room Temperature 27°C.
3	Applicator of Fig. 2	2.30 ± 0.05, $d_o = 0$ 1.56 ± 0.03, $d_o = 6$	1.95 ± 0.10, $d_o = 0$ 1.55 ± 0.03, $d_o = 5.5$	1.80 ± 0.05, $d_o = 0$ 1.45 ± 0.06, $d_o = 6$	3. For each measurements, with no load, the applicator was matched to free-space by a slide-screw tuner.
4	Applicator of Fig. 2 with shallow grooves filled with dielectric	2.8 ± 0.06, $d_o = 0$ 1.6 ± 0.01, $d_o = 7$	2.3 ± 0.07, $d_o = 0$ 1.48 ± 0.09, $d_o = 7$	2.82 ± 0.07, $d_o = 0$ 1.32 ± 0.03, $d_o = 8$	4. With load, the off-set d_o was adjusted for minimum input VSWR

This is due to a reduction in edge diffraction because of curvature in the disk [8]. Also, the leakage power via minor lobes, in this plane, constitutes only about 20 percent of the power in the main lobe when the disk is curved. However, this percentage enhances to 28, when the disk is flat. 3) By using a curved disk in place of a flat one, the on-axis gain is altered to a slight extent (0.2 dB). It is indicated in [8] that the on-axis gain of the test-applicator (Fig. 1) increases (and consequently the beam width decreases) if the radius of curvature R_0 is decreased. However, a small value for the radius of curvature is not recommended because of problems that may arise while machining the corrugations on the disk. As a design compromise, R_0 is chosen to be approximately 5λ in the present work as well as in [6]–[9]. 4) For the applicators shown in Figs. 1 and 2, the corrugated disks (flat and curved) were replaced by disks of shallow corrugations filled with a dielectric (paraffin wax, $\epsilon_r = 2.73$). The depth of the corrugations at $f = 9.47$ GHz is then equal to 4.9 mm as per (1). The measured near-field patterns for these applicators are shown in Fig. 4. These measured patterns are almost identical to those of the applicator depicted in Figs. 1 and 2. This proves the possibility of using dielectric-filled shallow-grooved corrugations without any adverse effects.

Pattern measurements presented here relate to the condition that the test applicator opens onto free space. In actual practice, the applicator is kept in contact with a biomedium so that the microwave energy is radiated into this medium and sets up a three-dimensional heating profile. Though the present measurements (due to restricted laboratory facilities) do not provide explicitly the heating patterns (such as those measured in the phantom models of [1]), the free-space results furnished here can, however, be directly correlated to such heating patterns.

Considering the input VSWR performance of the structures presented here (Figs. 1 and 2), measurements were carried out at a frequency of 9.47 GHz by loading the applicator (that is, by keeping in contact with the applicators) with the following selected portions (partial-body) of the biomedia (human) *in vivo*: 1) interior of the palm (medial palmar space); 2) upper outer quadrant of the left breast, and 3) cheek portion directly upon the zygomatic bone on the lower and lateral side of the orbit. Experiments were conducted on a cooperative adult subject who could hold the applicator firmly upon the test surface during the measurements. A low power level of microwave from a Gunn-diode oscillator source was maintained in the plumbing so that no possible radiation hazards were encountered. Measured average values of the input VSWR obtained by repeated measurements and the corresponding standard deviations are presented in Table I. From these results it can be observed that by off-setting the corrugated disk (flat or curved), the input VSWR can be made less than 1.6 when the applicator is in contact with a test surface *in vivo*.

Though the study undertaken here concerns itself with X-band applicators, the design principles can, however, be extended to other frequencies, such as, say, 2.45 GHz which is widely used in diathermy applications. Furthermore, as indicated in [1], the waveguide aperture can also be loaded with a dielectric material which allows the design flexibility of selecting a fairly wide range of aperture diameter $2a$.

Lastly, it is appropriate to suggest here that a better form of direct-contact applicator, as compared to the types discussed in the present work as well as in [1], is an open-ended corrugated pipe carrying the hybrid (HE_{11}) mode [12]. This radiator exhibits scalar-horn characteristics with excellent beam-symmetry properties in the principal planes and its edge-diffracted secondary fields tend to be zero. Furthermore, a simple design procedure, easy methods of hybrid-mode excitation and fabricational techniques are available for this structure. It can be designed to operate at a desirable microwave frequency suitable for diathermy purposes. Aperture size compatible with frequency and edge taper can be designed with known results [12]. One of the authors had earlier used this hybrid-mode aperture loaded with a dielectric sphere [13]–[16] and with a dielectric hemisphere [17] to realize focused beams suitable for noninvasive, selective (partial-body) irradiations; and research is already in progress to study the behavior of this radiator (corrugated pipe) as a direct-contact type of applicator. Calculations on heating patterns and input admittance characteristics while in contact with and/or offset from a multilayered biomedium are being carried out for this hybrid mode structure and the results will be published later.

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Microwave Power Absorption in a Biological Specimen Inside a Standing-Wave Irradiation Waveguide

OSAMU FUJIWARA AND YOSHIFUMI AMEMIYA

***Abstract*—An irradiation system consisting of a standing-wave in a waveguide is a convenient way to study biological effects of the individual components of the microwave fields. This paper describes microwave power absorption in a biological specimen exposed to standing waves inside the waveguide with a reflection plate. A method is presented to obtain the absorbed power distribution and total power absorption in a prolate spheroidal model of a specimen having small dimensions compared to the guide wavelength. Numerical results on the pupa of Tenebrio molitor are given, and also verified experimentally.**

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I. Introduction

In investigating biological effects and potential hazards of electromagnetic (EM) radiation, many detailed theoretical analyses of the EM power absorption in various tissue-equivalent models have recently been performed. In this type of analysis, either plane-wave irradiation in free space [1]–[5] or traveling-wave exposure in waveguide [6], [7] has usually been considered, and thus electric and magnetic fields were assumed to interact simultaneously with the biological tissue.

Of particular interest here are interactions of individual electric and magnetic field components of microwave fields with the tissue, for which no theoretical analyses have previously been made.

In order to investigate separately the effects of the electric and magnetic fields on biological specimens such as animal, insect, bacteria, etc., a standing-wave irradiation waveguide system is convenient. This paper presents a method for calculating the absorbed power density and total absorbed power in such specimens modeled as prolate spheroids inside the waveguide with a reflection plate, when the guide wavelength is long compared to the spheroidal dimensions.

Numerical calculations on the Tenebrio pupa, which has often been used to study the microwave biological effects [8]–[11], are given as an example, and the results are compared with experimental measurements.

II. Theory

A. Standing-Wave Irradiation Waveguide

Fig. 1 shows a standing-wave irradiation system using a rectangular waveguide. Biological specimens are mounted in styrofoam and inserted along the center line of the waveguide at half intervals of a guide wavelength λ_g.

In terms of the rectangular coordinates shown in Fig. 1, standing-wave fields inside the empty waveguide which operates in TE_{10} mode can be written by

$$\mathbb{E}_s = (-j2E_f)\cos(\pi x/a)\sin\left[2\pi(z-d)/\lambda_g\right] \cdot \exp(j\omega t - j2\pi d/\lambda_g)\hat{y}$$

$$\mathbb{H}_s = (-2E_f/\eta_0)(\lambda/\lambda_g)\cos(\pi x/a) \cdot \cos\left[2\pi(z-d)/\lambda_g\right]\exp(j\omega t - j2\pi d/\lambda_g)\hat{x} + (-2E_f/\eta_0)(\lambda/2a) \cdot \sin(\pi x/a)\sin\left[2\pi(z-d)/\lambda_g\right]\exp(j\omega t - j2\pi d/\lambda_g)\hat{z}$$

where $\mathbb{E}_s$ and $\mathbb{H}_s$ are electric and magnetic field vectors, respectively. η_0 is the free-space intrinsic impedance, λ is the free-space wavelength, and ω is the angular frequency. E_f represents the amplitude of the incident electric field, which can be calculated simply from $E_f = 2\sqrt{(\lambda_g/\lambda)(P_f \cdot \eta_0/ab)}$ where P_f is a forward power into the waveguide. $\hat{x}$, $\hat{y}$, and $\hat{z}$ are the unit vectors in the x, y, and z directions, respectively.

When the biological specimen has dimensions small enough compared to the guide wavelength λ_g and the waveguide width a, the specimen placed at the origin is exposed to the following

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