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On the Design of Dielectric Loaded Waveguides

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Abstract—**Rectangular waveguides partially filled with a dielectric slab in the E plane can provide an alternative to ridged waveguides in broad-band systems. It is shown that by an appropriate choice of the dielectric constant, maximum power handling capacity for a given bandwidth and cutoff wavelength can be achieved. This power handling capacity is much higher than for ridged waveguides. Attenuation and the effect of the first longitudinal-section-electric (LSE) mode on bandwidth are also discussed.**

INTRODUCTION

DIELECTRIC loaded waveguides have been investigated by a number of authors [1]–[6] in the past two decades. In particular, a rectangular waveguide loaded with a dielectric slab across its center, in the E plane, manifests attractive properties as a transmission medium: increased bandwidth, greatly increased power handling capacity, and relatively low attenuation.

For broad-band systems, ridged waveguides are currently in use. Their properties were analyzed in detail by Hopfer [7]; standard lines of ridged waveguides designed for fixed bandwidths and minimum attenuation are available. The potential advantage of dielectric loaded waveguides over ridged waveguides is in the power handling capacity. The purpose of this paper is to present a design procedure which maximizes the power handling capacity of dielectric loaded rectangular waveguides. It will be shown that for a given cutoff frequency, the maximum power handling capacity is obtained when a dielectric slab is chosen having the smallest dielectric constant consistent with the bandwidth requirements. This dielectric constant then determines uniquely the dimensions of the slab and of the waveguide. The resultant waveguide has a bandwidth, dimensions, and attenuation comparable to those of the ridged waveguide but a power handling capacity about six to seven times higher around the frequency of minimum attenuation.

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Previous work analyzed the propagation characteristics of the $TE_{n,0}$, longitudinal-section-electric (LSE), and longitudinal-section-magnetic (LSM) modes in the dielectric loaded waveguide. The present paper discusses in detail the characteristics of the first LSE mode and its effect on bandwidth.

THEORY

The geometry of the dielectric loaded guide under consideration is shown in Fig. 1. The modes which can propagate in this inhomogeneously filled waveguide are of two types [8]: LSE modes characterized by $E_x = 0$ and LSM modes with $H_x = 0$. LSE modes with no y dependence reduce to the ordinary $TE_{n,0}$ modes. The bandwidth of the loaded waveguide is normally defined as the ratio of cutoff frequencies of the TE_{20} to the TE_{10} modes. This has been discussed previously [3]; for convenience, we reproduce here (Fig. 2) bandwidth curves similar to those in that paper. The important conclusion to draw from these curves is that for a given bandwidth, a relative dielectric constant K' greater than a critical value must

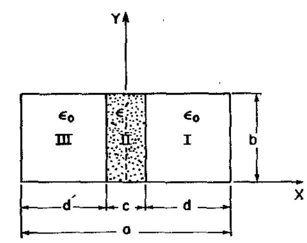


Fig. 1. Waveguide cross section.

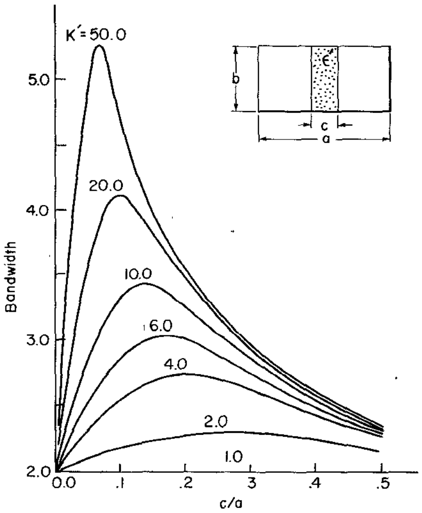


Fig. 2. Bandwidth fc_{20}/fc_{10} versus filling factor c/a for various dielectric constants.

be chosen. For example, for a bandwidth of 3, materials with a K' of at least 6 must be used for loading the waveguide.

If the cutoff wavelength of the first LSE mode falls within the band of interest, as defined by the TE_{10}–TE_{20} modes, the effective bandwidth will be reduced accordingly, unless some means for the suppression of the LSE modes is used. The occurrence of the first LSE mode within the TE_{10}–TE_{20} bandwidth is shown in Fig. 3(a)–(c). It is noted that interference of the LSE mode can be prevented by choosing a low enough b/a ratio. In fact, the bandwidth cannot be increased above 2 (empty waveguide) with $b/a = 0.5$ unless some LSE mode suppression method is used; however, choosing too low a b/a ratio results in increased attenuation.

POWER HANDLING CAPACITY

In order to discuss the power handling capacity of the loaded guide, it is first convenient to redraw the curves of Fig. 2 in the form of constant bandwidth curves as shown in Fig. 4. Thus a given bandwidth uniquely establishes a relationship between the relative dielectric constant K' and the dielectric filling ratio c/a.

The expression for the power carried by the TE_{10} mode in the loaded guide is given by [3] (using our notation)

$$P = \frac{ab\beta E_0^2}{4\omega\mu_0}\left[\frac{2d}{a}\left(\frac{\cos\theta_2}{\sin\theta_1}\right)^2\left(1-\frac{\sin 2\theta_1}{2\theta_1}\right) + \frac{c}{a}\left(1+\frac{\sin 2\theta_2}{2\theta_2}\right)\right] \quad (1)$$

where $\theta_1 = Ud$ and $\theta_2 = Vc/2$, U, V are the eigenvalues which govern the field distributions in the x direction in the air and dielectric region, respectively, β is the propagation constant for the TE_{10} mode, and E_0 is the electric field in the center of the guide. The maximum power which can be handled by the waveguide is determined by the breakdown of air at the position of the highest electric field, i.e., at the air–dielectric interface. This power is given by

$$P_{\max} = \frac{ab}{4\eta}\frac{\lambda}{\lambda_g}\frac{E_{bd}^2}{\cos^2\theta_2}Q(\theta_1,\theta_2) \quad (2)$$

where λ_g is the guide wavelength, $\eta = 120\pi\ \Omega$ is the free space impedance, E_{bd} is the breakdown field for air, and

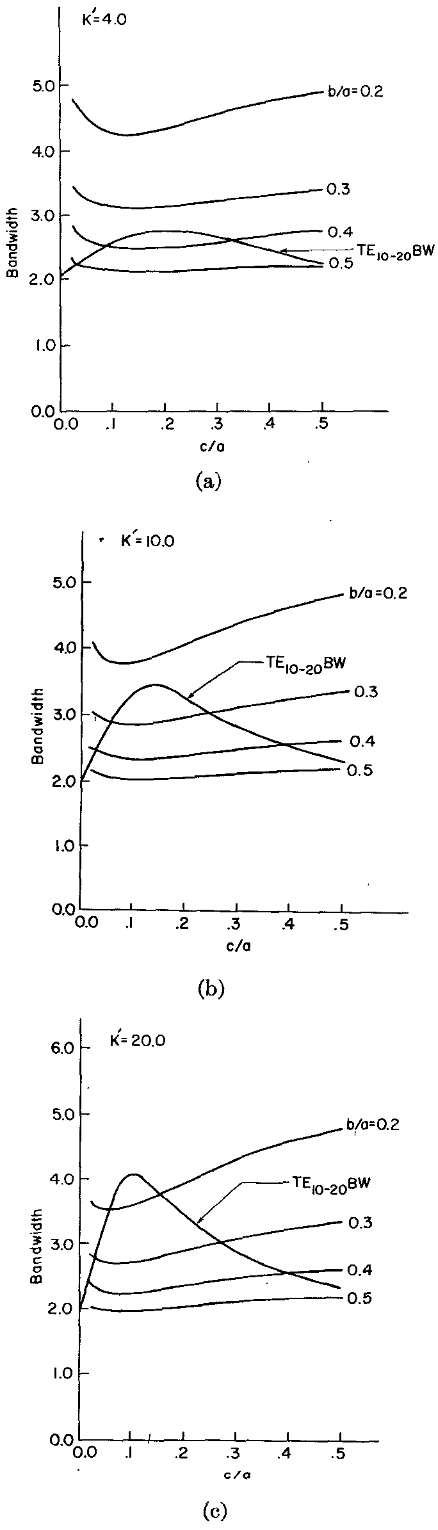


Fig. 3. Bandwidth as ratio of cutoff frequency of first LSE to TE_{10} mode. (a) $K' = 4.0$. (b) $K' = 10.0$. (c) $K' = 20.0$.

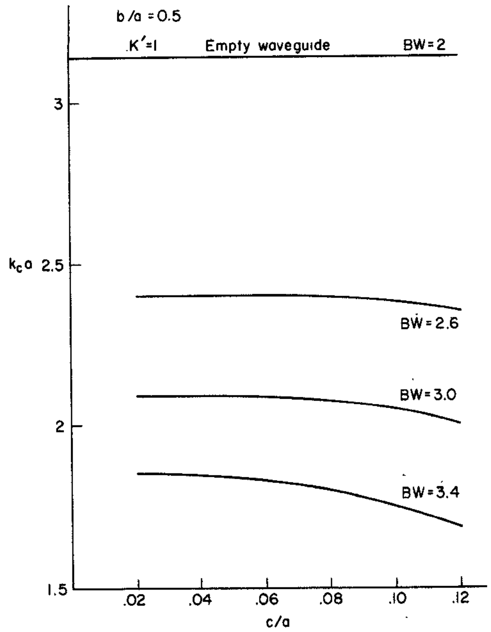


Fig. 4. TE_{10} mode normalized cutoff wavelength versus filling factor.

$Q(\theta_1,\theta_2)$ is the bracket in (1). The maximum power normalized with respect to the cutoff wavelength is given by

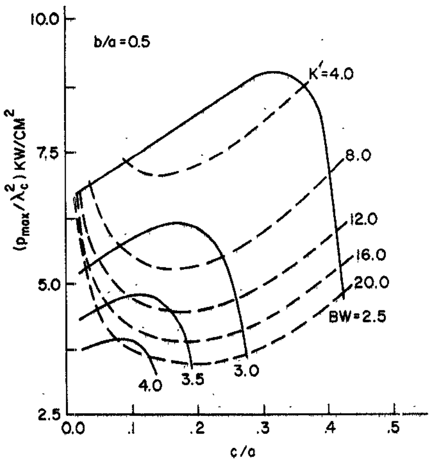
$$\frac{P_{\max}}{\lambda_c^2} = \frac{B}{4\eta}\left(\frac{a}{\lambda_c}\right)^2 \frac{\lambda}{\lambda_g} \frac{E_{bd}^2}{\cos^2\theta_2} Q(\theta_1,\theta_2) \tag{3}$$

where $B = b/a$ is the height-to-width ratio of the waveguide. Expression (3) is plotted in Fig. 5(a) and (b) at the frequencies 1.2 fc_{10} and fc_{20}. Note that the maximum power increases with frequency for a given cutoff wavelength; ridged waveguides behave similarly. Here it is primarily due to the concentration of power in the dielectric slab at increased frequencies, resulting in a reduced electric field at the air–dielectric interface.

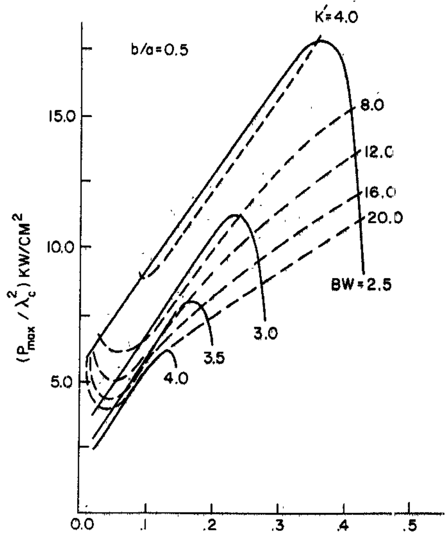
From Fig. 5(a) and (b) it is seen that for fixed bandwidth the maximum power handling capacity/(cutoff wavelength)^2 is reached at the minimum value of dielectric constant necessary to achieve that bandwidth. The optimum value of K' determines the ratio c/a, the normalized slab width. Choosing a value of K' slightly higher than the optimum results in two solutions for c/a. To minimize attenuation one should always choose the lower value for c/a. We have plotted on an expanded scale [Fig. 5(c)] the rising portion of the power handling capacity versus c/a curve evaluated at $f = \sqrt{3}fc_{10}$.

The design procedure for the dielectric loaded waveguide is now straightforward. For a given required bandwidth find the values of K' and c/a from Fig. 5(c). Find the corresponding value of $k_c a$ from Fig. 4. Knowing the required cutoff frequency, compute the maximum power $P_{\max}$, the guide width a, and height $b = 0.5a$.

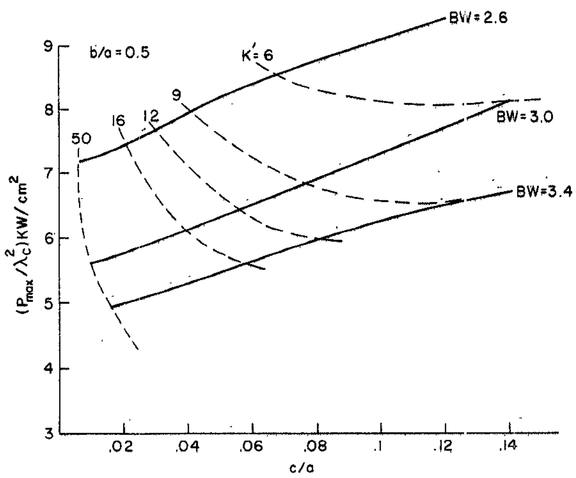
We have mentioned previously that for a given bandwidth and K' one should choose the lower value of c/a for reduced attenuation. This can be seen from Fig. 6



(a)



(b)



(c)

Fig. 5. Maximum power handling capacity. Breakdown field of air = 15 KV/cm. (a) $f = 1.2\ fc_{10}$. (b) $f = fc_{20}$. (c) $f = \sqrt{3}fc_{10}$.

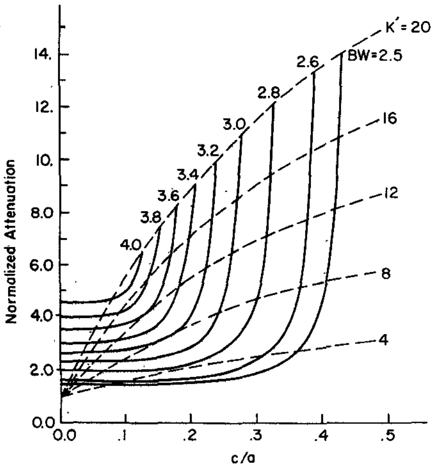


Fig. 6. Attenuation (due to wall losses only) normalized to empty rectangular waveguide of same cutoff frequency evaluated at $f = \sqrt{3}fc_{10}$. Material: copper.

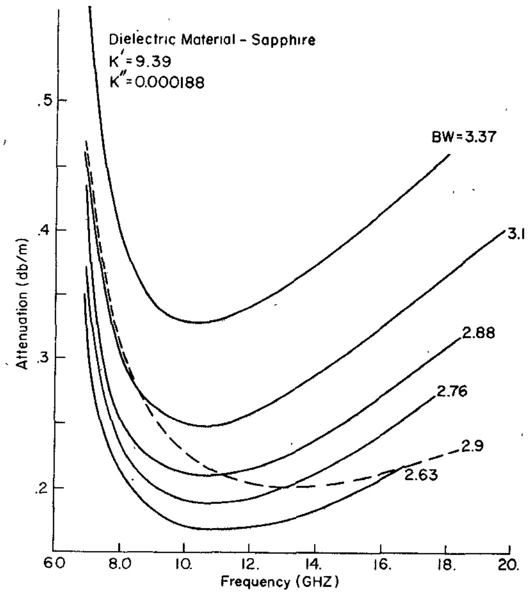


Fig. 7. Total attenuation (wall and dielectric losses) for dielectric loaded guide of same cutoff frequency as WRD750D24 double-ridged waveguide. Broken curve is for ridged guide. Wall material: aluminum.

where the normalized wall losses are plotted versus c/a. In as far as the dielectric losses are concerned, they are proportional to the loss tangent of the material. For a given tan δ of the material, the dielectric losses at the minimum loss frequency are rather insensitive to K' and c/a for constant bandwidth and cutoff wavelength. However, past the point of minimum attenuation the dielectric losses rise faster with frequency if the loading material has a higher dielectric constant. Thus the design which optimizes power handling capacity also achieves low attenuation and a low rate of change of attenuation with frequency.

In Fig. 7 we illustrate the attenuation of a rectangular waveguide loaded with sapphire $K' = 9.39$. For a bandwidth of 2.88 the attenuation is comparable to that of a

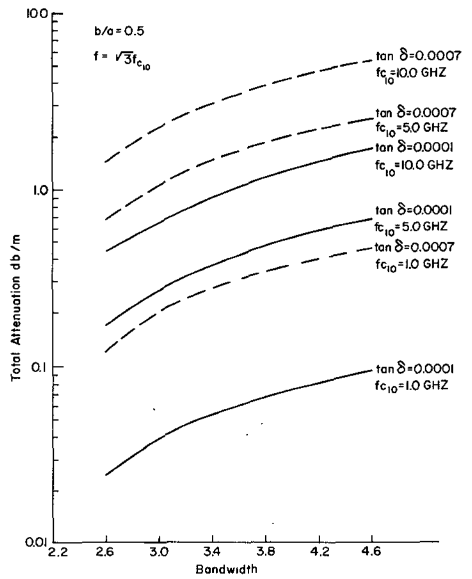


Fig. 8. Attenuation versus bandwidth for materials with various loss tangents. Wall material: copper.

double-ridged waveguide operating over the same frequency range. The power handling capacity of this dielectric loaded guide is about 160 kW as compared to 33.5 kW for the ridged waveguide. It should be noted that for an operating bandwidth of 2.4 which may require $fc_{20}/fc_{10} = 2.9$ the optimal value of K' is 5, in which case the power handling capacity could be increased to about 190 kW; simultaneously, the rate of change of attenuation with frequency would be reduced.

In Fig. 8 we present the computed attenuation versus bandwidth at $f = \sqrt{3}fc_{10}$ for waveguides loaded with dielectric materials having different tan δ and different cutoff frequencies.

CONCLUSIONS

Dielectric-loaded rectangular waveguides have greatly increased power handling capacity over ridged waveguides having the same bandwidth. This has been pointed out previously by researchers in the field. This paper describes a systematic procedure for achieving the high power handling capability of the loaded guide combined with low attenutation.

The design strategy consists of choosing a dielectric material with a K', which is the lowest required to achieve the desired bandwidth. This results in the widest loading slab for that bandwidth and cutoff wavelength. The attenuation at high frequencies is dominated by the dielectric losses; they can be minimized by the use of materials with a very low loss tangent. The low dielectric constant loading material chosen for power optimization will also reduce the rate of change of attenuation with frequency.

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Short Papers

A Probe for Measuring Temperature in Radio-Frequency-Heated Material

RONALD R. BOWMAN

***Abstract*—Measuring temperature in material being heated by radio-frequency (RF) fields is difficult because of field perturbations and direct heating caused by any conventional leads connected to the temperature sensor. A temperature probe consisting simply of a thermistor and plastic high-resistance leads appears to practically eliminate these problems. The design goals are described, and the performance of an initial test model of this type of probe is discussed.**

INTRODUCTION

For bioeffects research and the control of potentially hazardous electromagnetic fields, a need exists to measure temperature in subjects and models during exposure to intense fields [1]–[7]. This problem would be trivial except for the fact that conventional thermocouples and thermistors use leads that grossly distort the internal field structure and also produce intense heating directly due to the induced radio-frequency (RF) currents [1]–[7]. One solution to this problem utilizes fiber optics coupled to a liquid-crystal temperature transducer [6]. Another approach uses a prepositioned, electrically nonconductive well that allows rapid insertion of the temperature sensor after the field source is turned off [2], [4]. Others have developed a probe consisting of a Wheatstone bridge circuit, extremely fine electrodes connected to a thermistor, and high-resistance plastic leads [5]. The temperature probe described here also uses a thermistor but is simpler in design (see the next section) and should produce considerably less heating (due to the use of higher resistance leads). As of this writing, parts are being obtained and fabricated to construct a probe with a 1-mm-OD tube, a thermistor with dimensions less than 0.5 mm, and high-resistance plastic leads with resistances of about 160 kΩ/cm.[1] This short paper describes the test results for a probe that was made from parts that were immediately available. Since this initial model of this type of probe has much greater sensitivity, stability, and dynamic range than the probe described in [6], it is believed that these early test results are of interest.

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[1] *Note Added During Review:* This probe has been fabricated. It has a response-time constant of less than 0.2 s, short-term stability better than 0.01°C, and a high-resistance-line heating error (see section on experimental tests) of less than 0.005°C for a heating rate of 1°C/min.

PROBE DESIGN AND CONSTRUCTION

As shown in Fig. 1, the probe consists simply of two pairs of very-high-resistance leads connected to a small high-resistance thermistor (about 750 kΩ at 25°C and a coefficient $\simeq -0.04/°C$). The thermistor resistance is sensed by injecting a constant current through one pair of leads and measuring the voltage developed across the thermistor by means of a high-impedance amplifier connected to the other pair. If the current generator and amplifier have high impedances compared to the leads, the thermistor can be measured accurately despite the large and unstable lead resistances. This technique is commonly used when the lead resistance is significant, but in the present application the lead resistances will typically be 10 MΩ rather than the usual lead resistances that are of the order of 10 mΩ. The main difficulties in realizing good probes of this type are fabricating high-resistance lines with lineal resistances of 100 or more kilohms per centimeter and attaching these leads reliably to the thermistor.

Leads with the required high resistance can be made by either thick- or thin-film processes, but it may be difficult to make long leads using these processes. The present probe design uses plastic high-resistance leads developed earlier for use with electromagnetic hazard meters [8], [9]. For the initial test model, the cross section of the leads is about 0.25 by 0.25 mm and their lineal resistance is about 40 kΩ/cm. The leads are bonded to the thermistor with silver-loaded epoxy.

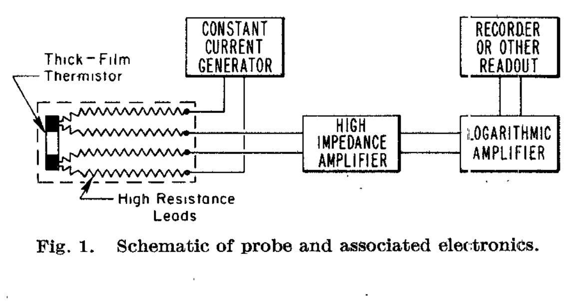

Fig. 1. Schematic of probe and associated electronics.