A Hybrid Dielectric Slab-Beam Waveguide, Theory and Experiment

Dr. J.W. MINK*
U.S. Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709

Dr. F.K. SCHWERING
U.S. Army CECOM, ATTN: AMSEL-RD-ST-C, Ft. Monmouth, NJ 07703

Dr. P.L. HERON, Mr. G.P. MONAHAN, Mr. A. SCHUENEMANN,
Mr. S. ZEISBERG, Dr. M.S. STEER
Dept. of Elec and Comp Eng., NCSU, Raleigh, NC 27695-7911

Abstract

A hybrid dielectric slab-beam waveguide is presented which is well suited for the design of planar quasi-optical integrated circuits and devices operating in the millimeter and sub-millimeter wave band. Planar quasi-optical systems have the distinct advantage over other techniques that they can be photolithographically defined and that lateral-dimension tolerances are greatly relaxed, thus leading to easy production. In addition, active sources and passive control elements may be integrated into the guiding medium. The new guide consists of a grounded dielectric slab into which a sequence of equally spaced cylindrical lenses is fabricated. (The center line of the slab guide is the axis of the lenses). The structure uses two distinct wave guiding principles in conjunction with each other to guide electromagnetic waves. In the direction normal to the slab surface, the guided fields behave as surface waves of the slab guide; their energy is largely confined to the interior of the dielectric and they are guided by total reflection at the slab surface. In the lateral direction the waves behave as Gauss-Hermite beammodes that are guided by the lenses which periodically reconstitute their cross sectional phase and amplitude distribution, resulting in a wave beam that is iterated with the lens spacing. The theoretical part of the paper presents analytical expressions for the modes of the guide. The experimental part reports on an open, quasi-optical resonator derived from the new guide, confirming the theory and demonstrating the usefulness of the resonator for quasi-optical power combining of solid-state sources.

A Hybrid Dielectric Slab-Beam Waveguide, Theory and Experiment

Dr. J.W. MINK*
U.S. Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709

Dr. F.K. SCHWERING
U.S. Army CECOM, ATTN: AMSEL-RD-ST-C, Ft. Monmouth, NJ 07703

Dr. P.L. HERON, Mr. G.P. MONAHAN, Mr. A. SCHUENEMANN,
Mr. S. ZEISBERG, Dr. M.S. STEER
Dept. of Elec and Comp Eng., NCSU, Raleigh, NC 27695-7911

1. Introduction

Dielectric waveguides such as image guide and insular guide are low-loss lines that are well suited as transmission media for the design of integrated circuits and devices operating in the mm-wave region. To avoid overmoding, the width of these guides typically will be chosen somewhat less than a half wavelength in the guide material. A problem is at the small wavelengths in the upper mm-wave and sub-mm-wave regions the guide width becomes exceedingly narrow and the guides incorporating active elements become very difficult to fabricate. The hybrid dielectric slab-beam waveguide discussed in this paper solves this problem by employing a quasi-optical guidance principle to provide beam-confinement in the lateral direction. This permits one to choose the width of the guide to be electrically large. Fig. 1 shows the configuration of the proposed guide. It consists of a thin grounded dielectric slab of rectangular cross section, into which a sequence of equally spaced

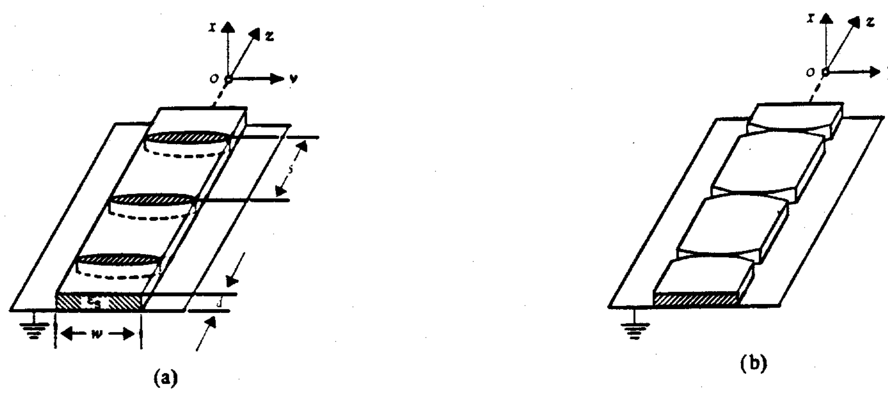

Fig. 1 Hybrid dielectric slab-beam waveguide. The cylindrical lenses embedded in the slab periodically refocus the guided fields. The lens shape is convex for $\epsilon_{lens} > \epsilon_{slab}$, case (a), and concave for $\epsilon_{lens} < \epsilon_{slab}$, case (b).

cylindrical lenses is embedded. The convex shape of the lenses depicted in Fig. 1a applies to the case that their permittivity exceeds that of the guide. In the opposite case, the lenses will have the concave shape sketched in Fig. 1b. "Air lenses" of this type may simplify fabrication and reduce diffraction losses.

The guide uses two different waveguiding principles in conjunction with each other to confine and guide electromagnetic waves. The important characteristics of the modes of the dielectric slab-beam waveguide can be summarized a follows:

(1) In the direction normal to the slab surface (x-direction) the modes behave in the fashion of surface wave modes of the dielectric slab. They are guided by total reflection at the air-dielectric interface, their energy is largely confined to the interior of the dielectric, and their magnitude decreases exponentially away from the slab.

(2) For the lateral direction (y-direction) the modes show the behavior of Gauss-Hermite beammodes. They are guided by the sequence of phase transformers that are inserted in the slab and periodically re-set the cross sectional phase distribution of the modes. The field distribution of each mode is periodic with the spacing of the lenses.

(3) The propagation constant of the modes in the longitudinal direction (z-direction) equals k_o at cutoff and approaches k_s with increasing frequency. It is always within the range $k_o < \beta_n < k_s$ thus characterizing the modes as surface waves of the dielectric slab. While conventional beam waveguides are virtually non-dispersive, the modes of the dielectric slab-beam waveguide show the dispersion of the dielectric slab guide.

(4) The modes of the dielectric slab-beam waveguide form a system of orthogonal modes that allows the complete description of any wave beam guided by the structure. While individual modes are periodic with the spacing of the phase transformers, this is not necessarily the case for a wavebeam consisting of several modes. With each iteration the modes are multiplied by an iteration factor Γ_{nm} which depends on the mode numbers n and m, and the amplitude spectrum of the composite beam will vary from guide section to guide section.

The quasi-optical guidance principle implies that the width w of the guide should be in the order of, at least, several λ_ε and may be as large as hundreds of λ_ε, so that the guide has a reasonable width and is easy to fabricate. In addition, the field distribution of the modes is virtually independent of w, and side-wall tolerance requirements are greatly relaxed.

The waveguide should be useful in particular for the sub-mm-wave region of the electromagnetic spectrum. Combining structural simplicity, approaching that of a slabguide with the increased lateral dimensions of quasi-optical guides, it should be easy to fabricate and show good electrical performance. In addition, bends and transition are easily implemented in this guide by standard quasi-optical techniques while causing minimum radiation loss and mode conversion; and guide sections operated as open resonators should be well suited for the design of quasi-optical power combiners that may contain numerous solid-state sources and could serve as single-mode high-power sources for these waveguides [1].

2. Theory

The idealized dielectric slab-beam waveguide of Fig. 2 consists of a grounded dielectric slab of permittivity ε_s and width $w \rightarrow \infty$. In the planes $z=(2\mu-1)z_t$, with $\mu=1,2..$, planar phase transformers are inserted in the guide; these phase transformers are assumed to extend to infinity, both in the x- and y- dimensions, and similar to cylindrical lenses introduce a phase shift $\Delta\Phi$ in the transmitted fields that is quadratic in y and uniform in x.

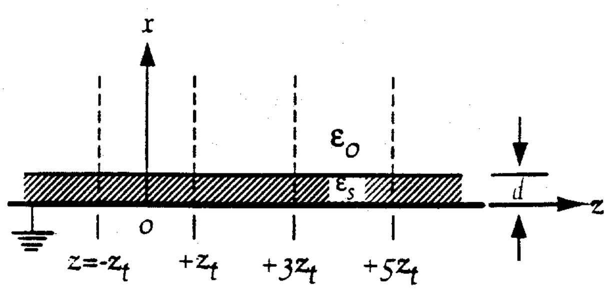

Fig. 2 Idealized dielectric slab-beam waveguide with equally spaced infinitely thin phase transformers that provide a quadratic phase correction in the y-direction. It is assumed that the lateral width of the slab is infinite and that the phase transformer dimensions are unbounded both in the x- and y-direction.

The modes of this waveguide are derived by combining the theory of the dielectric slab guide with that of the beam waveguide. The resulting theory may be described as a modification of the theory of conventional beam waveguides in which the beammodes no longer are formulated as narrow two-dimensional bundles of elementary plane waves but as narrow one-dimensional bundles of surface wave modes[1] of the slab guide. A detailed presentation of the theory [2] would go beyond the scope of this paper and we restrict ourselves here to summarizing the results.

There are two groups of these modes. The first group has the significant field components E_x, E_z and H_y and is in effect TM-polarized with regard to the direction of propagation (z-

---

[1] We are interested here in fields that are guided by the dielectric slab-beam wave and therefore consider only the surface modes of the slab guide, while the radiative wave which describe scatter and radiation effects can be disregarded in the present context.

direction), while the second group is TE-polarized having the significant field components E_y, H_x and H_z [2]. In the space range $-z_t < z < +z_t$ the field distribution of the modes takes the form, for the TE modes:

$$E_y^{n,m} = -\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{k_0}{\beta_n} H_x^{n,m} = G_n(x) Q_{nm}(y,z) e^{-j\beta_n z}$$
$$H_z^{n,m} = \frac{1}{j\beta_n}\frac{\partial H_x^{n,m}}{\partial x} \tag{1}$$
$$n = 0,1\cdots N, \qquad m = 0,1\cdots\infty$$

where N is the total number of surface wave modes supported by the dielectric slab.

Corresponding formulas are obtained for the TM modes but for concieness, are not shown here. The x-dependence of the modes $G_n(x)$ is that of the surface wave modes of the (uniform) slab guide and may be found in [2, 3] while the y-dependence (which varies with z) is that of a Gauss-Hermite beammode [4, 5].

$$Q_{nm}(y,z) = Q_m(y,z;v_n,\beta_n) = \sqrt{2\pi}\frac{v_n}{\left[1+\left(\frac{v_n^2}{\beta_n}z\right)^2\right]^{\frac{1}{4}}}$$
$$\cdot\ He_m\left\{\frac{\sqrt{2}\,v_n y}{\left[1+\left(\frac{v_n^2}{\beta_n}z\right)^2\right]^{\frac{1}{2}}}\right\}$$
$$\otimes \exp\left\{-\frac{1}{2}\frac{v_n^2 y^2}{1+\left(\frac{v_n^2}{\beta_n}z\right)^2} - j\left[\frac{1}{2}\frac{v_n^4\frac{z}{\beta_n}y^2}{1+\left(\frac{v_n^2}{\beta_n}z\right)^2} - \left(m+\frac{1}{2}\right)\tan^{-1}\left(\frac{v_n^2}{\beta_n}z\right)\right]\right\} \tag{2}$$

Note that similar to the case of conventional beam waveguides the focal length f of the lenses has to exceed $z_t/2$ for iteration (and guidance) to occur. The propagation constants β_n are determined by the well known dispersion relations of the dielectric slab [3] and are in the slow-wave (surface wave) region

$$k_o < \beta_n < k_s$$

Equations (1) and (2) give the field distribution of the modes in the guide section $-z_t < z < +z_t$ between two adjacent phase transformers. This field distribution is periodic with the spacing $2z_t$ of the phase transformers and repeats itself from guide section to guide section, except that with each iteration the modes are multiplied by a factor Γ which depends on the mode numbers n and m. For the idealized, loss less guide of Fig. 2, Γ_{nm} is a pure phase factor and its absolute value is unity. Actual guides of finite cross section dimensions will show an iteration loss and $|\Gamma_{nm}|$ will be smaller than 1. As a general rule, the iteration loss will increase with the mode numbers n and m. For any plane z- constant., the modes of the dielectric slab-beam waveguide are orthogonal and any field that is guided by the structure can be expanded into a series of these modes.

The theory discussed so far assumes an idealized, lossless guiding structure with infinite cross sectional dimensions as indicated in Fig. 2. The finite dimension of actual guides will modify the field distribution of the modes and cause an iteration loss. A discussion of these effects can be found in [2] where also, an estimate of their magnitude is given.

3. Experimental Results

Experimental verification of the hybrid dielectric slab beam waveguide (HDSBW) was conducted by simulating a long propagation path using open resonator techniques. As is well known, the propagation factor and field distribution of any transmission line may be measured by using a resonator to simulate many iterations of the transmission medium. The resonator consists of one guide section terminated at each end by a reflector shaped to correspond to the phase front of the propagating beam in the respective plane. The resonant frequencies are determined by the condition that the z-dependent phase shift of the mode traveling from one reflector to the other is q π where q is an integer. Since, this phase shift is a function of mode number, a discrete spectrum of modes exists for each q.

An experimental HDSBW resonator of the type suitable for quasi-optical power combining is shown in Fig. 3. Designed for operation at X-band, the resonator was used here to verify the existance of Gauss-Hermite beammodes in the HDSBW and to investigate field distortions and interation losses caused by the finite dimensions and tolerancees of the guide. The present paper expands on the results reported in [1].

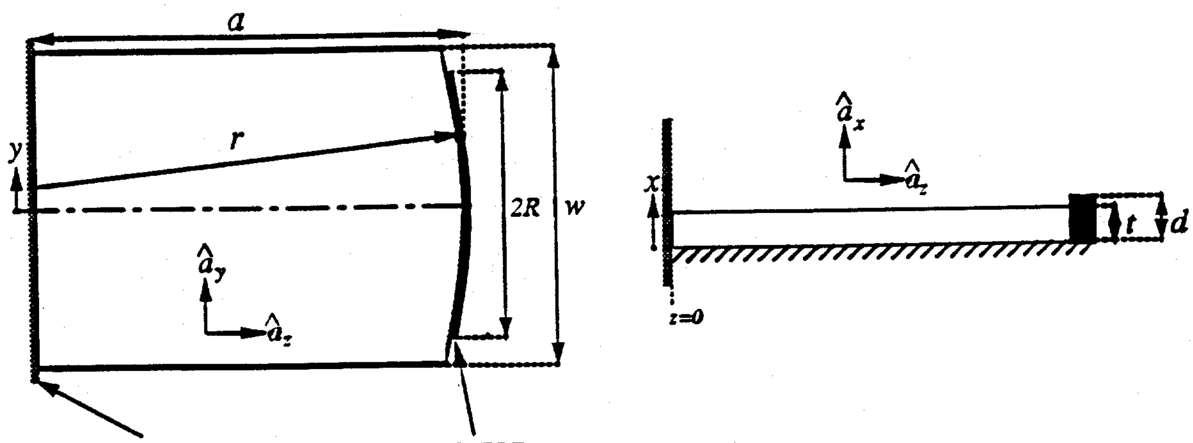

Fig. 3: HDSBW resonator. The dielectric in Rexolite: $\varepsilon_r = 2.57$, $\tan\delta = 0.0006$
$a = 30.48$ cm, $b = 38.10$ cm, $r = 60.96$ cm, $t = 01.27$ cm.

The resonator was excited by a small antenna placed parallel to the planar reflector and embedded in the dielectric. The antenna was small enough to ensure that it loosely coupled to the resonator mode and did not distort that mode. The first step in the characterization process was determining the modes in the cavity and the Q of each resonance. It was found that the TE and TM modes could be selectively excited by placing the antenna parallel or perpendicular to the ground plane respectively. The results for the TE case are summarized in Figs. 4-5. Similar results were obtained for the TM case.

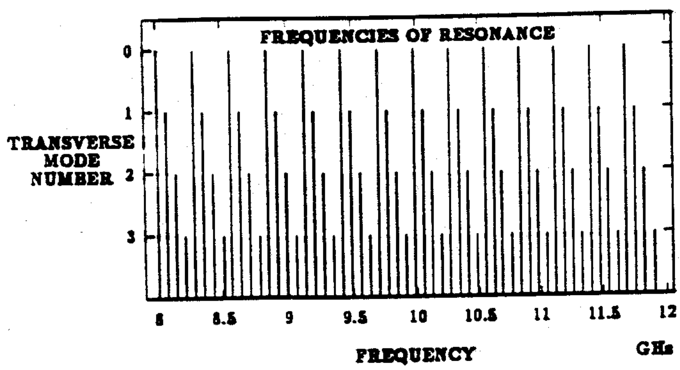

Fig. 4: Frequencies of the observed TE mode resonances with the antenna Parallel to the ground plane.

The observed resonance frequencies were in agreement with those predicted but for an error of 0.18% (15MHz) in the worst case, occurring at the lower end of the useful frequency band. This error can be accounted for by a small frequency dependence of the dielectric permittivity of Rexolite.

The measured quality factor Q of the TE mode resonances increases with frequency and peaks at a value of 2240 at 11.5 GHz. This can be compared to the published loss tangent of 0.0006 for Rexolite at X-band which corresponds corresponds to a Q of 1667. This is an upper limit on Q of the slab resonator and is modified by additional losses due to the grounded copper plane but with reduced dielectric losses as a part of the beam energy is guided outside the slab. The lateral dimension of the slab resonator was chosen to be three times the beam waist (between the 1/e field points) of the fundamental Gaussian beam mode at the lower limit of the frequency range, so as to minimize side-wall effects.

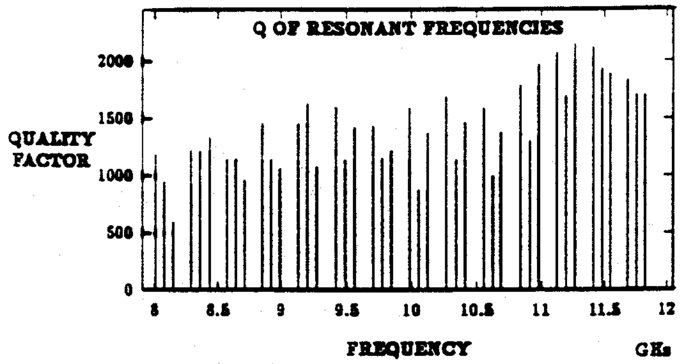

Fig. 5: Q of the lower frequency TE mode resonances with the antenna parallel to the ground plane.

The tranverse field profiles at resonance of the lower order modes of the q=27 family of the TE modes were measured and plotted, superimposed on Gauss-Hermite functions. Figure 6 shows typical reslult. The measurements and calculations were performed at a distance of 14 cm from the planar reflector.

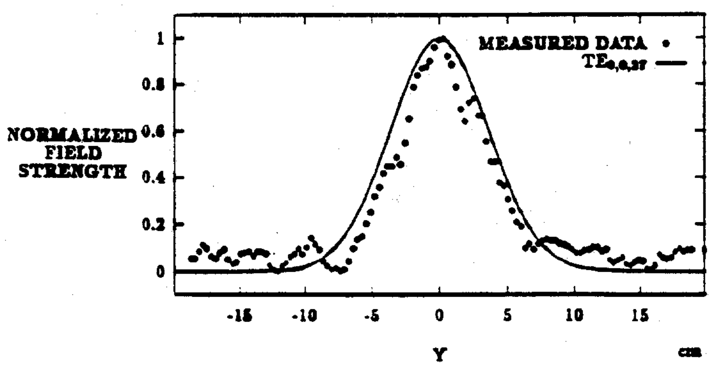

Fig. 6: Measured and calculated field profile of the lowest frequency TE mode (at resonance): $TE_{0,0,27}$ (9.986 GHz).

The relative field strength was measured as the change in the reflection coefficient as a small pyramid of lossy material was moved across the surface of the slab. An alternative method of determining the field profile would be to move the excitation source. However the method used here is perferred since, with the excition source fixed, the mode structure is as little disturbed as possible. For the TE0,0,27 and TE0,2,27 modes the antenna was placed at the y=0 position as then these modes are efficiently excited. For the TE0,1,27 mode a field null occurs at y=0 and so the field profile of this mode was made with the antenna at y= -2.54 cm. The profiles of these modes were in good agreement with the ideal Gauss-Hermit functions, see Fig. 6. thus confirming the theory. The side lobes are assumed to result from radiation modes of the HDSBW and additional TM-modes. Another factor of influence is the finite size of the reflector resulting in diffractions at the edges and changing the border conditions of the field propagation. Placing tapered wedges at the slab edges did not change the field profiles significantly, indicating that the HDSBW fields were independent of side-wall tolerances.

4. Conclusion

The HDSBW bridges the gap between conventional dielectric wave-guides used at millimeter wave frequencies and the slab type dielectric waveguide used at optical frequencies. It appears that the behavior of the fields in a HDSBW resonator is similar to that in an open resonator. The major difference is that most of the energy of the modes is confined to the dielectric region. With an open cavity, efficient and robust power combining is accomplished in three dimensions. In the planar slab resonator, power would be combined in two dimensions and the Q of the resonances, though still high will be limited by the inherent losses of the dielectric slab, the conduction losses of the ground plane and the useful energy coupled from the resonator. Nevertheless the hybrid dielectric slab beam waveguide should be well suited as a transmission medium for the design of planar quasi-optical integrated circuits and devices operating in the millimeter-wave and submillimeter-wave region. The HDSBW resonator should be the appropriate means for power combining in these regions since it is a planar device with (electrically) large lateral dimensions and relaxed tolerances. In future systems, passive and active devices can be introduced by selectively metalizing the back conductor of the resonator to form coupling aperatures or radiating elements. Figure 7 shows a prototype quasi-optical dielectric slab resonating power combinor that is currentyl under investigation. First experiments have demonstrated that the power of four MESFET sources could be combined in a highly stable fasion.

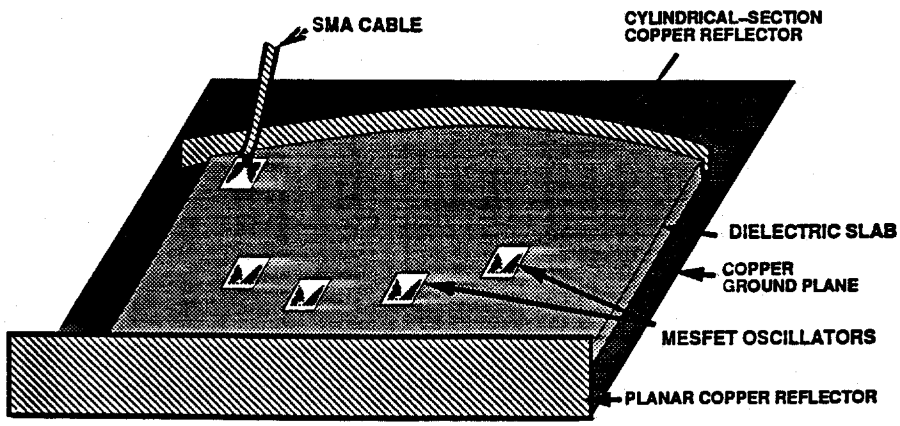

Fig. 7: Prototype quasi-optical slab resonating power combiner.

References:

[1] S. Zeisberg, A. Schunemann, G.P. Monahan, P.L. Heron, M.B. Steer, J.W. Mink and F.K. Schwering
Experimental investigation of a quasi-optical slab resonator,
IEEE Microwave and Guided Wave Letters, Vol. 3, August 1993

[2] J.W. Mink and F.K. Schwering
A Hybrid Dielectric Slab-Beam Waveguide for the Sub-Millimeter Wave Region, IEEE Transactions on Microwave Theory and Techniques,
Vol. 41, pp 2, Oct. 1993

[3] R.E. Collin
Field Theory of Guided Waves, Second Edition
IEEE Press, New York, 1991

[4] G. Goubau and F. Schwering
On the Guided Transmission of Electromagnetic Wavebeams
IRE Transactions on Antennas and Prop., Vol. AP-9, pp 248-256, 1961

[5] F. Schwering
Reiterative Wavebeams of Rectangular Symmetry
Archiv der Elektr. Uebertragung Vol. AEU-15, pp 555-564, 1961