Experimental Investigation of a Quasi-Optical Slab Resonator

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***Abstract*— A quasi-optical slab resonator for TE modes was experimentally characterized to demonstrate a planar technology for quasi-optical devices. Predicted and measured frequencies of resonance of the TE slab modes and electric field profiles are in close agreement.**

I. Introduction

Quasi-optical propagation is an attractive means for routing signals at millimeter-wave frequencies and above. This is partly because lateral dimensions are relaxed and because waveguiding is not dependent on metallic conductors which become excessively lossy at these frequencies. Instead signals propagate in a dielectric medium and are periodically refocused using lenses and/or reflectors [1], [2]. Almost all of the functions available in conventional (conductor-based) waveguiding are available by placing functional components in the quasi-optical beam [2], [3]. Complete quasi-optical signal processing systems however cannot be photolithographically defined thus limiting mass production and contributing to high cost. With the aim of developing a waveguiding medium which is more amenable to photolithographic reproduction and also with reduced size, Mink and Schwering have proposed a hybrid dielectric slab-beam waveguide (HDSBW) [4]. This structure combines the wave-guiding principles of dielectric surface waves and the confined beam corresponding to Gauss–Hermite beam modes. In this letter, an experimental investigation of the mode structure and field profiles of several modes of a HDSBW resonator, Fig. 1 is reported.

II. Slab Beam Modes

The HDSBW uses two distinct waveguiding principles in conjunction with each other to guide electromagnetic waves. In the direction normal to the slab surface the guided waves should behave as surface waves of the slab guide; their energy largely confined to the interior and near the surface of the dielectric with the electric and magnetic field strengths exponentially tapering off into the air region. In the lateral direction the waves should behave as Gauss-Hermite beam modes which are reflected by the curved reflector. A HDSBW supports TE- and TM-slab beam modes, defined with respect to the direction of propagation. The mode families are TE_{mnq} and TM_{mnq} where m, n, and q are the mode indices in the normal (x), transverse (y) and longitudinal (z) directions. For the resonator of Fig. 1 with the L-shaped antenna parallel to the ground plane a large number of resonant responses were observed for different longitudinal and transverse mode numbers of the TE modes. In this case, weaker and lower Q TM mode responses were detectable. With this antenna orientation, TE modes are preferentially excited while the excitation of the TM modes is poor. With the L-shaped antenna rotated so that it was normal to the ground plane TM mode resonances were larger but the TE responses were weak compared with the parallel antenna orientation. The transverse order of the modes was determined by field profiling. The resonant frequencies of the observed TE modes are plotted in Fig. 2 with the L-shaped antenna parallel to the ground plane.

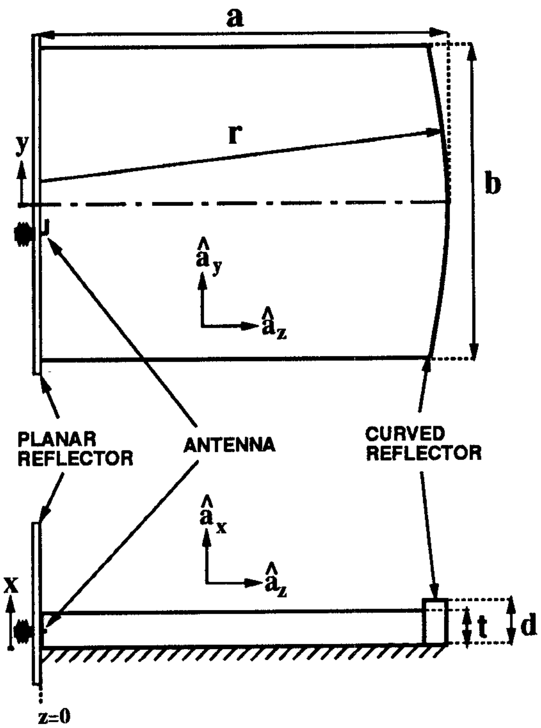

Fig. 1. Planar quasi-optical slab resonator: HDSBW resonator, the dielectric is Rexolite ($\epsilon_r = 2.57$, $\tan\delta = 0.0006$ at X-band), $a = 30.48$ cm, $b = 38.10$ cm, $r = 60.96$ cm, $t = 01.27$ cm.

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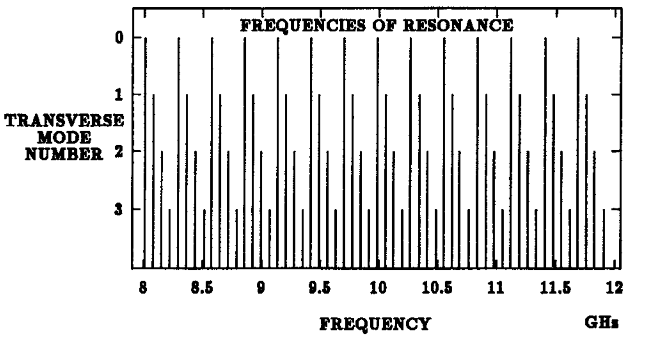

Fig. 2. Observed TE-mode resonant frequencies for various transverse modes.

The measured quality factor Q of the TE-mode resonances increases with frequency and peaks at a value of 2240 at 11.5 GHz. The published loss tangent of 0.0006 at X-band of the Rexolite dielectric [5] corresponds to a Q of 1667 in this frequency range. 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.

III. Frequencies of Resonance

The propagation constant, β_{nq}, of the TE_{0nq} resonant modes of the semi-confocal HDSBW resonator is [4, (27), (29)]

$$\beta_{nq} = \frac{1}{a}\left(q\pi + \left(n + \frac{1}{2}\right)\frac{\pi}{4}\right). \tag{1}$$

This is related to the resonant frequency of the TE_{0nq} mode by [6, (46)]

$$\sqrt{\beta^2 - \left(\frac{2\pi}{c}f\right)^2}\tan\left(d\sqrt{\epsilon_r\left(\frac{2\pi}{c}f\right)^2 - \beta^2}\right) = -\sqrt{\epsilon_r\left(\frac{2\pi}{c}f\right)^2 - \beta^2}. \tag{2}$$

These equations were numerically solved to obtain the TE_{0nq}-mode resonant frequencies f_{0nq}. Using a constant relative permittivity of 2.57 [5] for X-band results in a difference between measured and calculated resonant frequencies except in the center of the frequency range; apparently because the relative permittivity, ϵ_r, depends on frequency. The decrease of ϵ_r with increasing frequency [5] yields a relative error in the prediction of the frequencies of resonance of the HDSBW resonator of 0.18% (15 MHz) in the worst case, occurring at the lower limit of X-band.

IV. Mode Profile

The field profiles at resonance of the lower order transverse modes of the $q = 27$ family of the TE modes are depicted in Fig. 3 superimposed on Gauss–Hermite functions. The measurements and calculations were performed at 14 cm from the planar reflector in the z-direction. 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. For the $TE_{0,0,27}$ and $TE_{0,2,27}$ modes, the antenna was placed at the $y = 0$ position as then these modes are efficiently excited. For the $TE_{0,1,27}$ 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 main lobes match the Gauss–Hermite functions and verify the assumed model of wave beam propagation predicted by Mink and Schwering [4]. 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. Putting tapered wedges at the slab edges did not change the field profiles significantly.

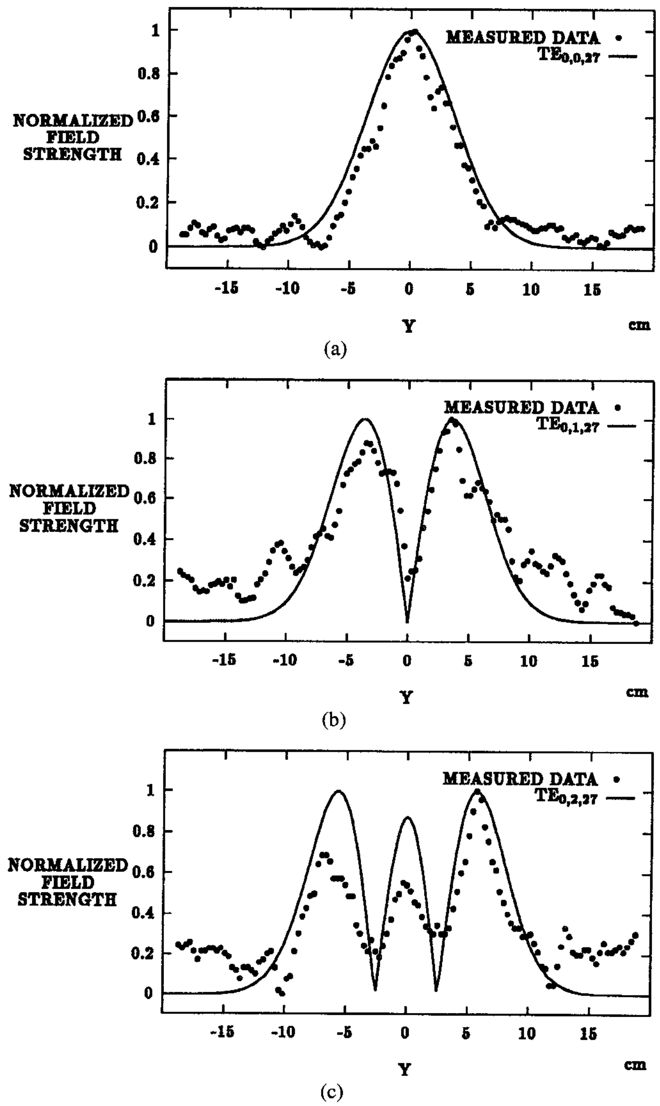

Fig. 3. Measured and calculated field profile of the lowest frequency TE modes (at resonance): (a) $TE_{0,0,27}$ (9.986 GHz), (b) $TE_{0,1,27}$ (10.056 GHz), (c) $TE_{0,2,27}$ (10.126 GHz).

V. Discussion and 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 in the fields 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 with the Q of the resonances less due to the inherent losses of the dielectric and conduction losses of the ground plane. 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 regions. The HDSBW resonator should be the appropriate means for power combining in these regions as lateral dimensions are relaxed in just one dimension and passive and active devices can be introduced by selectively metalizing the surface or, utilizing lamination, interior surfaces of the slab.

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