Phase Step Beam Waveguide

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Abstract—Experimental tests on a new type of beam waveguide constituted by a series of equispaced dielectric frames are described. Field-pattern and power-loss measurements have been performed on short-circuited sections of the waveguide working at 10 GHz and on the 37-GHz prototype constituted by Teflon square frames. In comparison with the more common iris and lens beam waveguides, it presents advantages concerning diffraction, reflection, and dissipation losses. In addition, it is lightweight and compact.

The experimental results confirm these advantages, along with a low sensitivity to assembling and constructive imperfections.

Design criteria are suggested as a result of the optimization for the lowest losses obtained through numerical computations performed on the equivalent open resonator.

I. Introduction

THE BEAM WAVEGUIDE is a means of electromagnetic power transmission that appears particularly suitable at millimeter wavelengths where conventional waveguides become inefficient.

The beam waveguides, first described by Goubau and Schwering [1], are periodic structures which allow the energy guidance by reconstruction of the beam at periodic intervals. Such reconstruction is possible only for beams whose field distributions are adapted to the guiding structure and constitute the so-called "beam modes" similar to those of the conventional pipe waveguides. The most common types are the iris and lens waveguides [2]–[4]. The iris type consists of a sequence of equispaced identical apertures in absorbing screens. The beam reconstruction is accomplished by limiting its cross section broadened by diffraction during the trip between a screen and the successive one. In such a waveguide, the losses are essentially due to the amount of energy intercepted by the screen; hence, the iris aperture must be large in wavelengths in order to minimize the diffraction. In the lens-type waveguide, the reconstruction is performed by transformation of the cross-sectional phase distribution achieved by means of dielectric lenses placed across the irises. Here the losses are mainly due to dissipation and reflection of the lenses, while the diffraction losses due to the limited aperture are negligible, as the beam is concentrated in the central region of the lenses.

A useful method for studying the properties of the beam waveguides is that of considering the equivalence between them and open resonators which can be seen as short-circuited sections of a beam waveguide [2], [3], [5], [7], [8]. Iris and lens beam waveguides have their equivalent in the planar and curved-mirror Fabry–Perot (FP) open resonators, respectively.

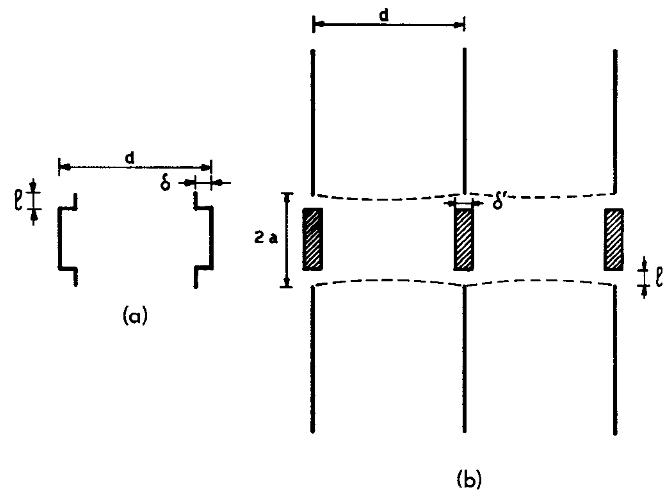

Fig. 1. (a) Cross sections of the step-rim open resonator. (b) Equivalent beam waveguide. Positive rim thickness.

The present paper is concerned with a new type of beam waveguide, whose elements are simple dielectric frames [9], which is derived from the rimmed open resonators extensively investigated by some of us [10]–[12]. The rimmed resonator is an FP terminated by plane mirrors with a step rim along the edges [Fig. 1(a)]. Due to the presence of the rim, the losses of the different modes change and present an oscillating periodical trend when the rim thickness varies with periodicity $\lambda/2$. The corresponding beam waveguide is constituted by a series of identical irises in absorbing screens, while the mirror rims are replaced by equivalent phase jumps. This phase jump can be obtained by placing a slab of dielectric material across the iris aperture leaving an empty area that corresponds to the rim of the mirror [Fig. 1(b)]. Of course, the rim thickness and the equivalent phase jump are so chosen as to correspond to a minimum loss. The periodical behavior of the losses, both for positive and negative values of the rim thickness, allows us to obtain the same minimum loss, but with a suitable negative rim thickness [Fig. 2(a)]. In this case, the equivalent beam waveguide is obtained by placing the dielectric material along the edge of the irises, thus leaving the central region empty [Fig. 2(b)]. Due to the presence of the rim, the field at the edges of the iris is extremely low, and consequently the absorbing screen can be removed without any appreciable perturbation.

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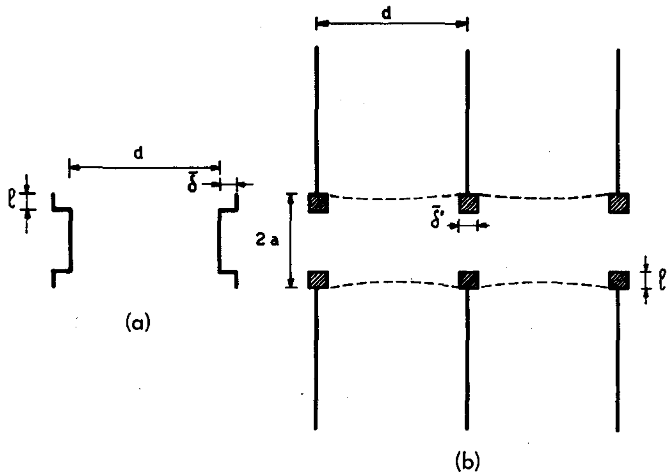

Fig. 2. (a) Cross sections of the step-rim open resonator. (b) Equivalent beam waveguide. Negative rim thickness.

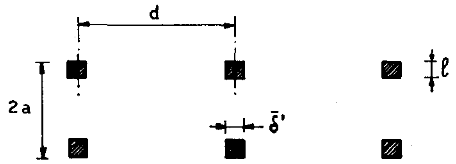

Fig. 3. Cross section of the dielectric frame beam waveguide.

The resulting structure is extremely simple and lightweight and is constituted by a sequence of equispaced frames (Fig. 3). In principle, these frames can have any shape, although the most practical ones are either square or circular.

Experimental tests have been performed on a resonating section working at 10 GHz and on a prototype working at 37 GHz. Optimization criteria have been obtained through numerical computations on the equivalent open resonator.

II. Experimental Tests

For the purpose of verifying the performance of the proposed beam waveguide, experimental tests have been carried out on sections of the waveguide that was short-circuited by two plane mirrors. Q's measurements and field-pattern recordings have been carried out at the resonant frequencies. The section was fed through a dielectric antenna protruding from the center of one mirror and connected to a standard X-band chain. The elementary cell of the waveguide consisted of two frames having dimensions $2a \times 2a = 28\lambda \times 28\lambda$ spaced by $d = 40\lambda$ (with a resulting Fresnel number $N = 5$). The frames were constituted by Plexiglass strips 1.67λ wide and 1.33λ thick which gave the phase jump corresponding to the minimum loss. The dimensions of the aluminum end mirrors were $2a \times 2a' = 28\lambda \times 52\lambda$. The Q's values for the lowest order mode, derived from the half-power width of the resonance curve [13], [14], were measured for resonating sections of different lengths or, in other words, short-circuiting a variable number of cells (Fig. 4). So doing, mirrors and coupling losses could be taken into account. For comparison, measurements have also been made on iris waveguide sections. Fig. 5 shows the losses derived from the Q's measurements versus the number of cells for the iris waveguide (dashed line) and for the frame waveguide (continuous line). The dotted-dashed line corresponds to the losses of a resonator having mirrors with the same dimensions as the frame aperatures and having spacing equal to that of the resonant section versus resonator length. For practical reasons it was impossible to test on longer resonant sections; however, the guiding effect of the frames is already evident as the corresponding loss curve tends to the steady slope trend, while the attenuation curve for the iris waveguide has already reached the steady trend with a higher slope. The attenuation derived from the final slope of the curve results in 0.035 dB/cell, which is lower by a factor of ~0.5 than that of the iris waveguide.

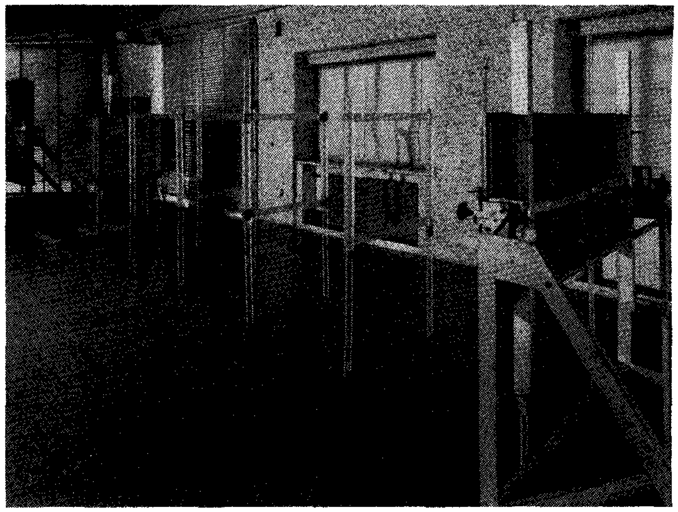

Fig. 4. The short-circuited section of the dielectric frame beam waveguide working at 10 GHz.

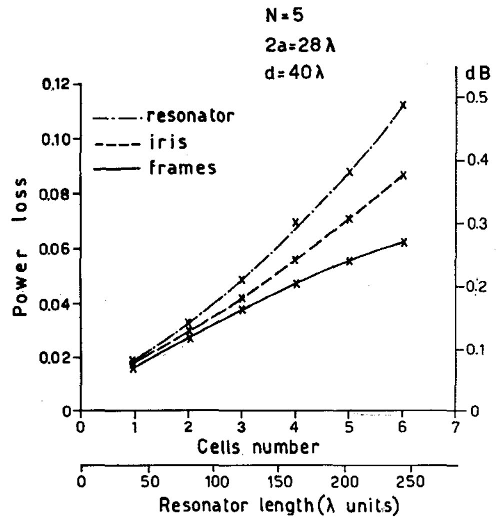

Fig. 5. Measured power loss versus cell number or resonator length for short-circuited sections of the iris waveguide (dashed line), frame waveguide (continuous line), and for the open resonator (dotted-dashed line).

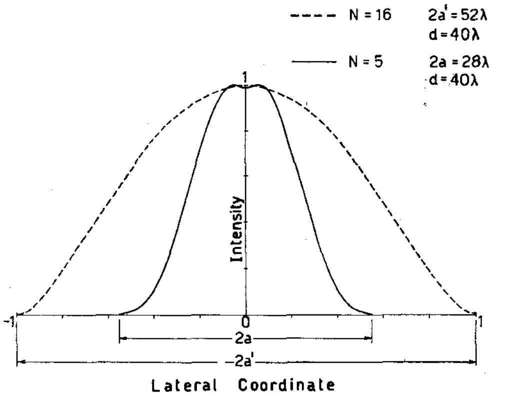

Fig. 6. Measured intensity patterns of the fundamental mode in the presence of the frames (continuous line) and in the absence of the frames (dashed line).

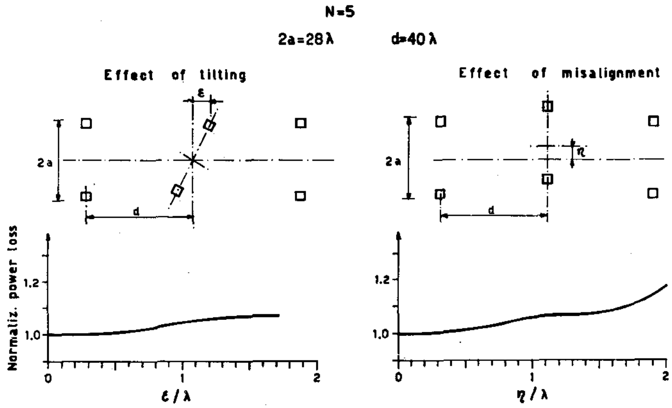

Fig. 7. Measured power losses versus the tilt sagitta ϵ and the amount of misalignment η.

Field configurations of the lowest order mode across the waveguide were obtained by the perturbation method [14]. Fig. 6 shows the measured intensity pattern plotted along the horizontal median line of a frame (continuous line) compared with the intensity pattern measured in the absence of frames. These patterns exhibit, once again, the confinement properties of the frames.

In order to verify the effect on the performance of construction and assembling imperfections, tests were carried out by tilting or misaligning one frame with respect to the other six frames. The curves of the normalized power losses plotted in Fig. 7 versus tilt sagitta ϵ and amount of misalignment η show a negligible increase up to values of ϵ and η of $\sim 2\lambda$.

Final tests have been carried out on a prototype of the frame waveguide working at 37 GHz. It is constituted by 53 Teflon square frames having the same dimensions in wavelengths as the above X-band model (Fig. 8). The launching of a sufficiently pure lowest order mode was accomplished by using an FP resonator with a semitransparent mirror having the same mirror aperture and spacing as those of the guide elements (Fig. 9). However, a small amount of higher order modes was still present giving rise to an interference between the considered mode and the immediately higher one, as the other modes are practically negligible. This can be observed in Fig. 10 where the field amplitude measured along the guide axis is plotted versus the frame number and is also confirmed by the field-pattern configurations measured along the horizontal median line across the guide aperture. Fig. 11 shows examples of such patterns in different positions along the waveguide from which the interference among the different modes results, as evident especially in the vicinity of the laucher. From the interference curve of Fig. 10 it is possible to derive an approximate value of

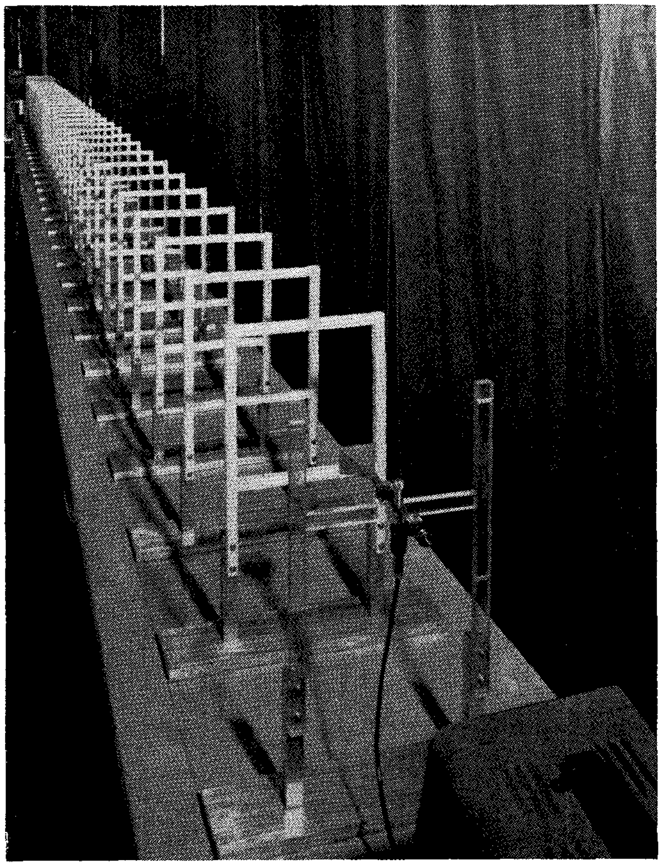

Fig. 8. The Teflon frame beam waveguide working at 37 GHz.

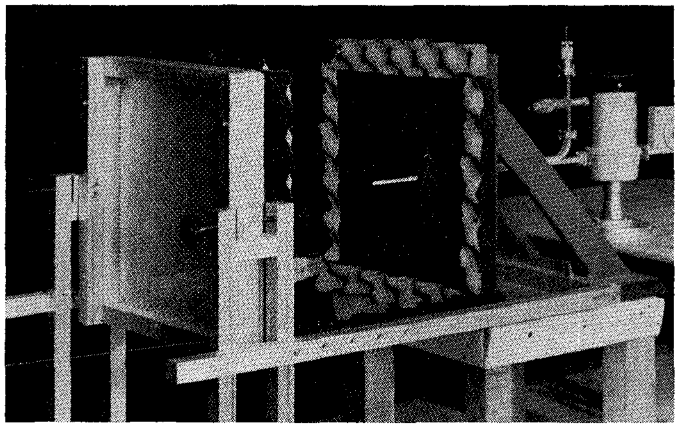

Fig. 9. The FP open resonator used as a launcher for the Teflon frame waveguide.

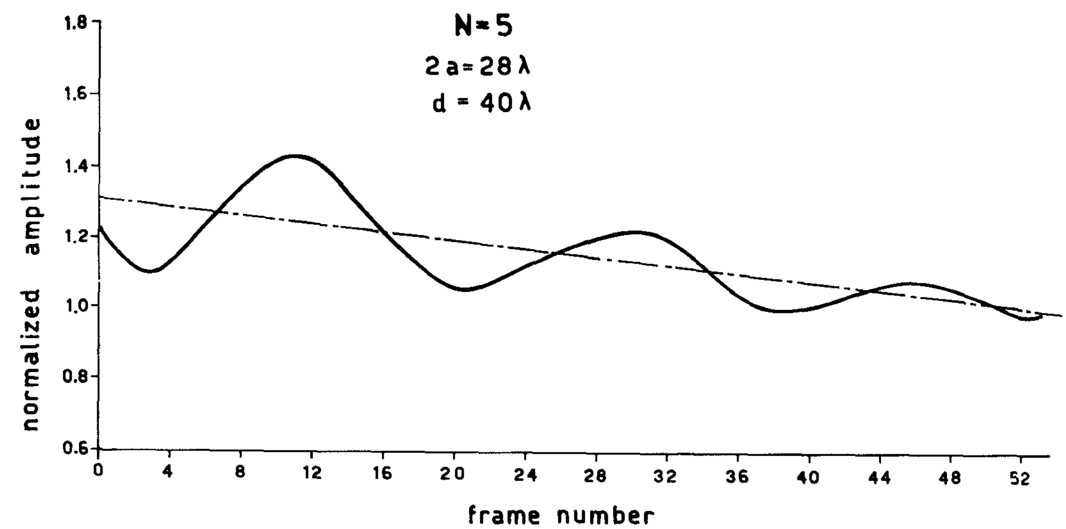

Fig. 10. The field amplitude measured along the axis of the 37-GHz beam waveguide.

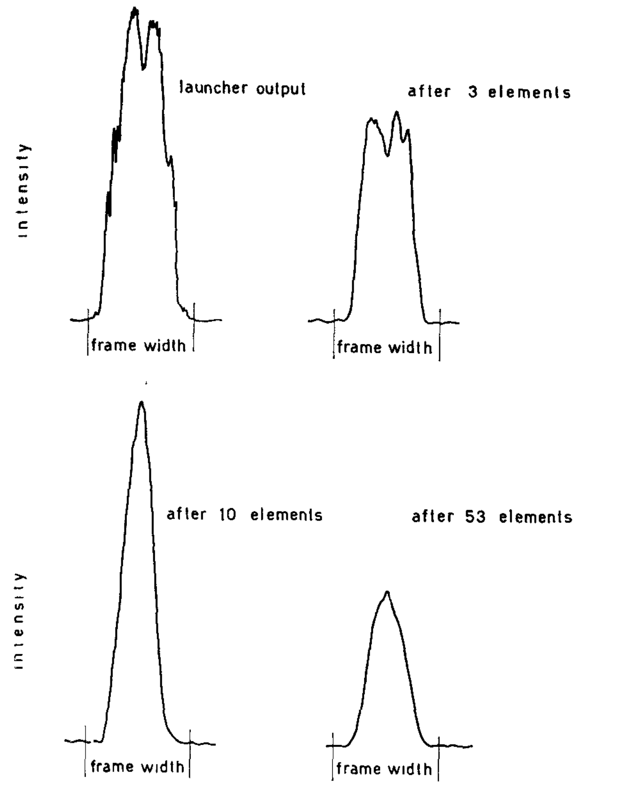

Fig. 11. Some examples of intensity field patterns measured at different distances apart from the launcher.

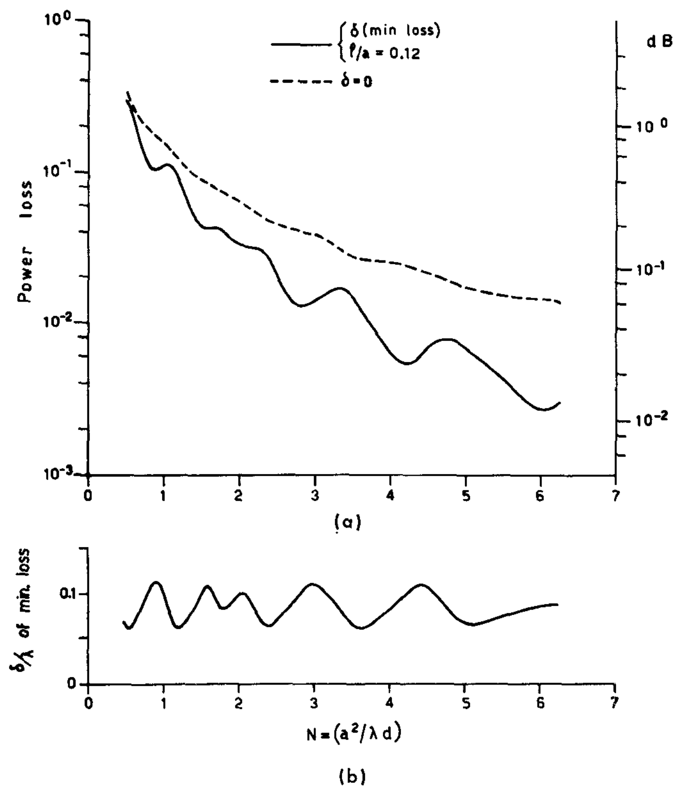

Fig. 12. (a) Computed minimum power losses. (b) Corresponding rim thickness. Equivalent open resonator plotted versus the Fresnel number in the case $l/a=0.12$. The dashed curve refers to the plane mirror FP resonator equivalent to the iris waveguide.

the attenuation for the fundamental mode which results in ~0.045 dB/cell, which is in good agreement with the values obtained with the resonant section and with numerical computations, as will be seen in the sequel.

III. Design Criteria

Some design criteria can be obtained by evaluating the losses of the lowest order mode of the equivalent step-rim resonator for different values of the Fresnel number and of the rim parameters. For this purpose, the integral equation relative to the considered open resonator was solved by numerical iterative procedure as described in [12].[1] The minimum losses obtainable for the resonator as functions of N for a constant value of the ratio l/a (rim width/mirror semiaperature) are shown in Fig. 12(a) (continuous line). These minimum

[1] In [12], the computations were carried out for the infinite strip resonator. In the present case, the losses for the square-mirror resonator have been accounted for by doubling the infinite strip loss values.

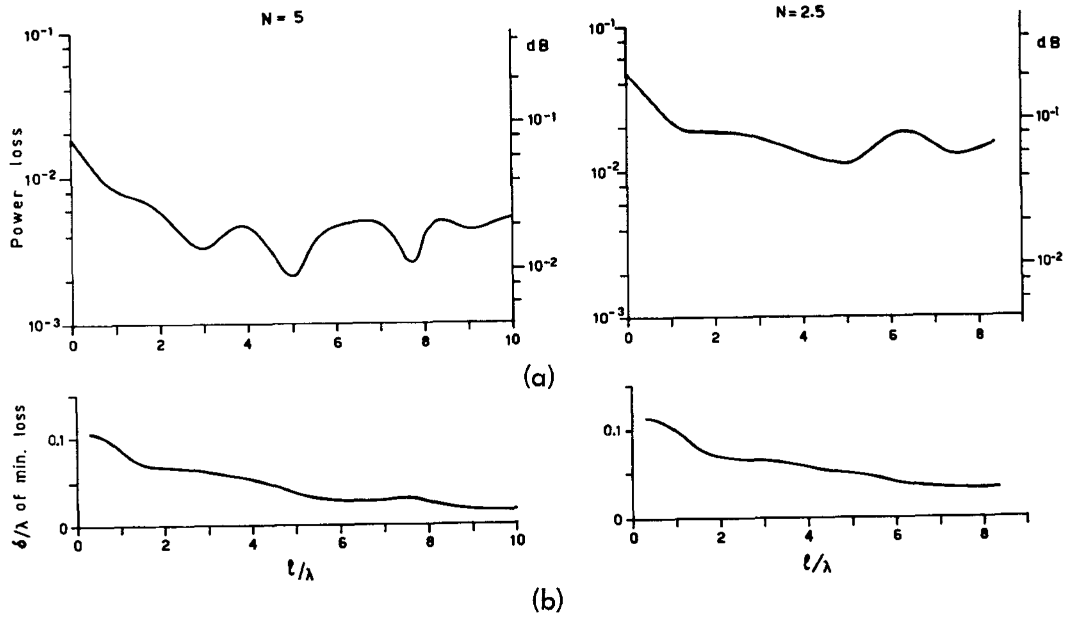

Fig. 13. (a) Computed minimum power losses. (b) Corresponding rim thickness. Equivalent open resonator plotted versus rim width for $N=5$ and 2.5.

losses were achieved by using the corresponding rim-thickness values plotted versus N in Fig. 12(b). For comparison, the losses of the FP resonator in the absence of the rims, which correspond to the iris waveguide, were also plotted versus N (Fig. 12(a), dashed line). The computed values for the power losses for $N=5$ results in 0.03 dB per transit, in good agreement with the measured values for the attenuation per cell. Further, we can note that even for smaller Fresnel numbers (down to $N=2.5$), the losses are limited within a reasonable value which would allow, for instance, the use of a smaller number of frames for a given waveguide length.

The influence of the rim width on the losses has also been examined in the two cases $N=5$ and 2.5, respectively. The upper curves of Fig. 13 show the minimum power losses which can be obtained when the rim width varies. The corresponding rim-thickness values (δ/λ) are plotted versus l/λ in Fig. 13 (lower curves). From these curves it turns out that for the tested prototype ($N=5$), the optimum strip width would be around $l=5\lambda$, while we used the value the $l=1.67\lambda$. However, when choosing the value of this parameter, one has to recall that the narrower the strip is, the lower the losses are for absorption and reflection of the dielectric material, so that a compromise must be achieved on the basis of absorption and reflection data of the considered dielectric.

In order to get an idea of the amount of energy impinging on the dielectric frame, the field distribution along the median line normal to the beam axis was computed. Fig. 14 shows the intensity pattern obtained starting from the previously computed mode distribution for the infinite strip (continuous line). The dashed line refers to the measured intensity distribution. One can observe that the bulk of the energy, which results proportional to the area below the curve, is confined within the frames; in fact, only 0.005 of the total energy is intercepted by the frame. This suggests that re-

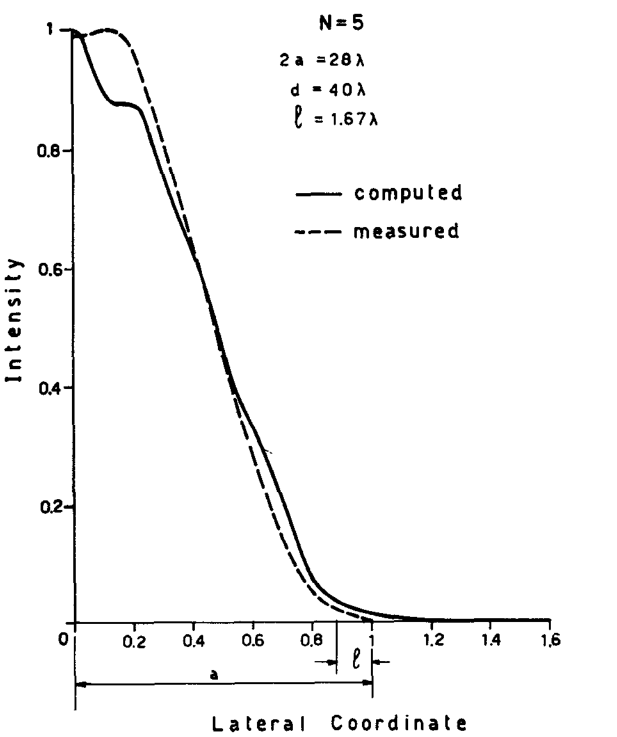

Fig. 14. Fundamental mode-intensity pattern computed along a median line perpendicular to the beam axis (continuous line) compared with the measured one (dashed line).

flection and absorption losses must be low and also that this waveguide is suitable for high-power transmission.

IV. Conclusions

The experimental tests reported in this paper have shown the feasibility and advantages of the new type of beam waveguide described. These advantages can be summarized as follows.

1) The diffraction losses are low in comparison with those of the iris type of the same dimensions. Also taking into account the dissipation and reflection losses due to the small amount of energy impinging on the dielectric structure, this type of waveguide can be competitive with the lens type, in spite of its lower diffraction losses. For the same reason, it is particularly suitable for high-power transmission.

2) This waveguide does not present difficulties in construction due to its low sensitivity to constructive and assembling imperfections.

Of course, the main applications of this waveguide are in the millimetric and submillimetric regions. However, due to its lightweight and simple structure, along with low loss even at reasonably small Fresnel numbers, application seems feasible also at decimetric and metric wavelengths.

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