I-4 A NEW CLASS OF LOW LOSS REACTIVE WALL WAVEGUIDES

R.P. Larsen

Grumman Aircraft Engineering Corporation

A.A. Oliner

Polytechnic Institute of Brooklyn

A novel approach is presented in this paper for achieving waveguides with especially low loss. This new class of waveguides employs "reactive walls", and has possible application to long waveguide runs in millimeter wave or high power systems. These reactive walls are designed by initially choosing them to be periodic structures, in the transverse directions, which are operated in their stop band or below cut-off condition. Because the transverse decay is high, the periodic structure can be truncated, and a simple, closed, final form results. The type of periodic structure chosen for investigation was an array of parallel dielectric slabs. Various practical low-loss reactive wall waveguides are then derived from this generic theoretical configuration.

A. "Reactive-Wall" Waveguides: Description and Method of Analysis

Initially, consideration was given to an infinite parallel-plate waveguide in which both conducting plates are replaced by identical, one-dimensional, semi-infinite, periodic structures (cf. Fig. 1(a)). The design parameters and frequency of excitation are chosen so that operation lies well within a stop band of both transverse periodically-loaded transmission lines. This causes the electromagnetic field to be rapidly attenuated in the x direction, perpendicular to the prescribed direction of propagation (the z-axis of Fig. 1). As a consequence, under lossless conditions, a purely reactive input impedance to the periodic structure is realized (hence the use of the adjective "reactive-wall").

The parallel plane configuration of Fig. 1(a) can support two types of modes, one for which the field contains only a magnetic field component perpendicular to the plane of the dielectric slabs, and the second for which this is an electric field component. These field types are referred to here as the transverse H-mode and transverse E-mode, respectively, and they correspond in an idealized parallel plate waveguide with metallic walls to the H_{10} and TEM modes (as the lowest modes of each type).

For either mode type, it is expected that when low-loss dielectrics are used the existence of a reactive-wall situation should result in an extremely small amount of energy dissipation. It is shown below that this reasoning is correct, and it is substantiated by the resulting comparatively small wave attenuation (over a reasonably wide frequency range of unimodal operation) associated with the reactive-wall waveguides investigated. The corresponding conventional waveguide, when it can support only the dominant mode, is used as a basis for comparison.

The derivation of the appropriate dispersion relation (for lossless dielectrics) is effected through the application of the transverse resonance technique. The complex propagation wavenumbers (for imperfect dielectrics) are then computed from their lossless counterparts by a first-order perturbation procedure.

Before an analysis of electromagnetic wave propagation in the structure of Fig. 1(a) can be initiated, the pertinent network characteristics of the infinite periodic waveguide must be ascertained. To this end, an equivalence is drawn between an infinitely long waveguide loaded periodically with dielectric slabs and a smooth transmission line (of characteristic imedpance $\hat{Z}_o$ and propagation wavenumber $\hat{k}_{xo}$). In this context, $\hat{k}_{xo}$ represents the wavenumber of the net traveling wave propagating through the infinite periodic structure (of characteristic impedance $\hat{Z}_o$). The network in Fig. 1(b) is thus an equivalent representation of the waveguide configuration of Fig. 1(a).

B. The Transverse H-mode Case

The theoretical analysis is initiated by applying the transverse resonance procedure to the equivalent circuit of Fig. 1(b). It is found that the resulting set of equations will have a non-trivial solution only when Z_o is a purely imaginary quantity and Z_o is purely real. This, of course, corresponds to the required stop band operation of the transverse periodic structures. Thus, the electromagnetic wave is evanescently attenuated along the direction of stratification.

Since typical values of the stop band decay rate are rather high (on the order of 15 db. per unit cell width, d), both semi-infinite periodic structures may be truncated after the first unit cell (for all practical purposes). Conducting plates may then be used to obtain a closed structure, as shown in Fig. 2(a). The validity of this simplification is illustrated in Fig. 3, wherein the dispersion curves A and C, associated with transverse H-mode propagation in the guides of Figs. 1(a) and 2(a), respectively, are observed to be practically coincident. Curves A and C were computed, respectively, from the equivalent networks of Figs. 1(b) and 2(b), using a systematic graphical method of solution. Since curve B of Fig. 3 represents the dispersion curve for the first higher mode, we note that a theoretical unimodal bandwidth greater than 2.3:1 is acquired with the structure of Fig. 1(a) (with $\epsilon_r' = 20$, $W/d = 3$, and $w/d = 0.75$). It might also be wondered if the air space between the dielectric slab and the metal in Fig. 2(a) is essential, or whether the somewhat simpler structure of Fig. 2(c) could serve as well. The fact that the latter is not a permissible substitute for the waveguide of Fig. 2(a) is clearly evidenced by dispersion curve D of Fig. 3, which applies to the structure of Fig. 2(c). It also turns out that the loss associated with the guide of Fig. 2(c) is much higher. The precise location of the dielectric slab away from the wall is therefore of considerable importance.

Having obtained the dispersion equation for the generic reactive-wall structure of Fig. 1(a), the attenuation constant a_z (which arises because the dielectric is slightly lossy) may be determined through the utilization of a first-order perturbation procedure. The results of such a calculation are portrayed in Fig. 4. In an effort to effect a fair comparison between the aforementioned reactive-wall waveguide and a conventional parallel-plate structure, the spacing between the copper conductors of the latter was chosen so as to provide unimodal operation over the 2:1 frequency band from 2175 Mc to 4350 Mc. Thus, at a frequency of 4350 Mc, both waveguides are at the cut-off frequency of their respective first higher order mode. The frequencies of 1880 Mc and 2175 Mc represent the cut-off values for the dominant mode in the reactive-wall and parallel-plate waveguide, respectively. Under these circumstances, the extremely low-loss characteristic of the reactive-wall waveguide is clearly shown in Fig. 4, where the attentuation of the conventional guide is more than four times that of the reactive-wall guide over a substantial frequency range.

It is mentioned in passing that the curve of a_z associated with dominant H-mode propagation in the truncated structure of Fig. 2(a) follows very closely the attenuation curve a_z of Fig. 4 (except in the vicinity of cut-off). This is to be expected since the contribution to the wave attenuation due to the metal walls is negligible compared to the dielectric loss (which, of course, is itself small) owing to the fact that all field quantities are evanescently attenuated transversely near the walls.

Finally, it should be noted that no great effort was made to achieve an optimal design with respect to wave attentuation and/or unimodal bandwidth of the reactive-wall waveguide.

C. The Transverse E-mode Case

The procedures and techniques used for the determination of the dispersion equation and attenuation characteristic of the reactive-wall wave-guide of Fig. 1(a) when operating in the dominant transverse E-mode are precisely the same as those presented in the previous section. Consequently, only a brief statement of the results will be given here.

It is found that the transverse decay rate of the fields is less in this case, so that two unit cells are necessary to establish an evanescent attenuation of approximately 16 db. Also, a relative attenuation a_c/a_z of between 3 and 4 was obtained over the frequency range considered previously.

D. Reactive-Wall Waveguide of Rectangular Cross-Section

The transverse E- and H-mode cases discussed above were combined to form the rectangular reactive-wall waveguide of Fig. 5. In an effort to facilitate the theoretical investigation of this structure, two valid (as was later experimentally ascertained) simplifying assumptions were made:

(1) the wave equation was taken to be separable in the cross-section, and

(2) the discontinuity susceptances, representing the junctions of the dielectric slabs, were neglected.

A typical value for the theoretical attenuation constant of this composite waveguide when it is operated near mid-band is given in Table I. The attenuation relative to that for empty rectangular waveguide of the same cut-off frequency for the second mode is also presented there for comparison. It is seen that the low loss properties are retained in this more involved structure, in which all four walls are of the "reactive" type.

TABLE I

RECTANGULAR REACTIVE WALL W/G.	RECTANGULAR W/G. (H_{10} MODE)
$a_z = 6.55 \times 10^{-3}$ db/m	$a_c = 21.2 \times 10^{-3}$ db/m

It should be noted that this attenuation value corresponds to a tan δ of 0.0006, which is available commercially at present. When better (lower loss) dielectric material will become available, the attenuation value will be still lower. Thus, although the rectangular reactive-wall waveguide is inherently more complicated to fabricate than its conventional counterpart, it may be designed to exhibit less loss (over certain reasonably wide frequency ranges) than the corresponding metallic guide, when the latter is operated in a unimodal fashion.

In order to verify the theory, the structure of Fig. 5 was constructed, and resonant frequency and Q measurements were taken on a section of this rectangular reactive-wall waveguide (in the form of a single-ended cavity). So as to minimize the relative attenuation effects of conductor and/or coupling losses, the guide was fabricated with rather lossy dielectric slabs. A comparison of the theoretical and experimental results is given in Table II.

TABLE II

	Resonant frequency	Unloaded Q	a_z (db/meter)
Theory	3000 Mc	500	0.642
Measurement	3000 ± 30 Mc	448 ± 25	0.716 ± 0.040

The rather good agreement between theory and experiment justifies the assumptions stated above regarding the theoretical analysis of the rectangular reactive-wall waveguide.

E. Reactive-Wall Waveguide of Circular Cross-Section

Since the rectangular reactive-wall structure is not easily constructed, one may wish to consider the circular guide of Fig. 6. Upon comparison with Fig. 2(a), is is clear that the basic behavior of the two structures will be similar when the circular guide is operating in the H_{01} mode, and the truncated guide in the dominant transverse H-mode. It should be recognized however, that in the case of the circular "reactive-wall" waveguide, a multi-mode situation is present, whereas throughout this paper we have concerned ourselves solely with single mode propagation.

Although we have not examined the behavior of the structure of Fig. 6 in detail, it would be expected that the loss associated with it should be less than found in circular waveguides of corresponding dimensions which are designed to carry the ordinarily low-loss circular electric mode.

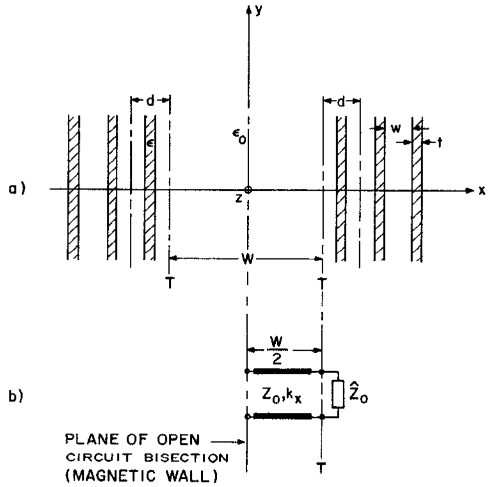

Fig. 1 - Parallel-plane reactive-wall waveguide employing two transverse semi-infinite transmission lines loaded periodically with dielectric slabs. (a) Physical configuration, (b) Equivalent network of bisected structure.

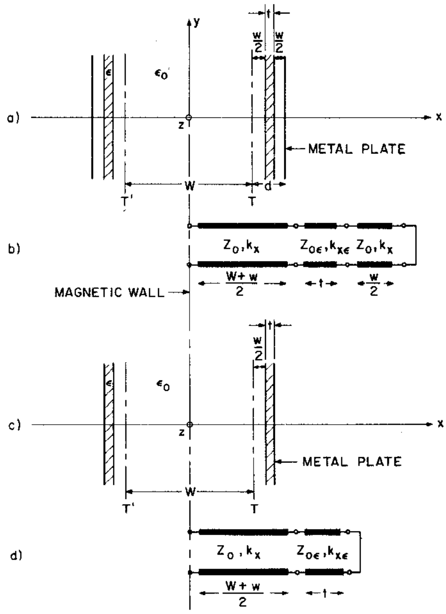

Fig. 2 - Parallel-plane reactive-wall waveguides (and their equivalent circuits) used to approximate the infinite structure of Fig. 1.

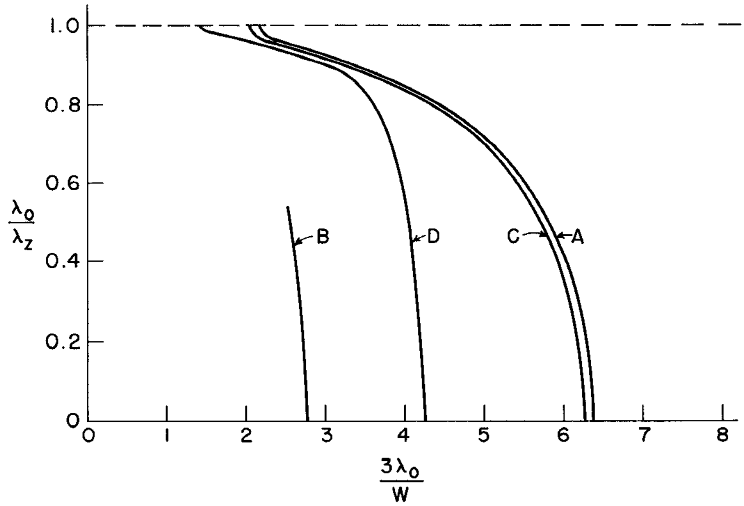

Fig. 3 - Transverse H-mode dispersion curves for various parallel-plane reactive-wall waveguides ($\epsilon_r' = 20$, $W/d = 3$, $w/d = 0.75$). Curves A and B: dominant and first higher order mode, respectively, in guide of Fig. 1(a). Curves C and D: dominant mode in guide of Fig. 2(a) and Fig. 2(c), respectively.

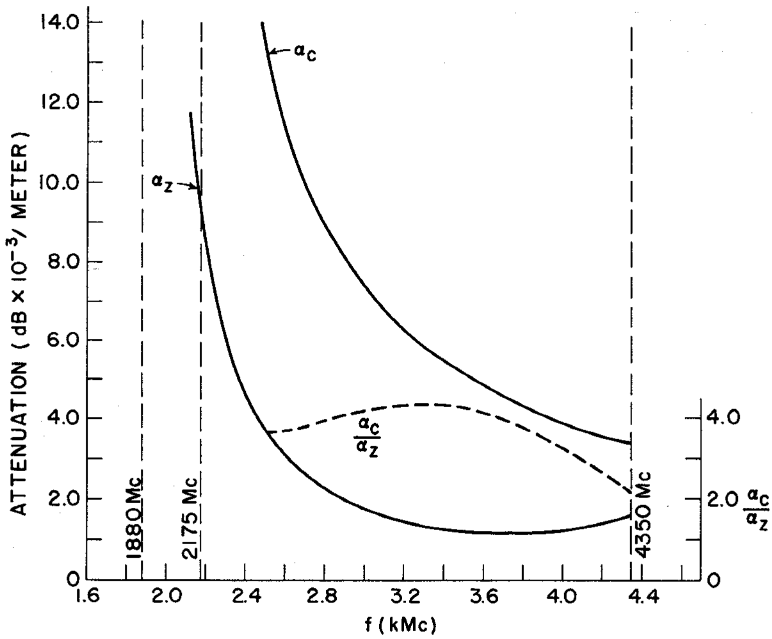

Fig. 4 - Comparative transverse H-mode attenuation vs. frequency curves for unimodal operation. α_z represents the dominant mode attenuation in the reactive-wall waveguide of Fig. 1(a) ($\epsilon_r' = 20$, W/d = 3, w/d = 0.75, d = 2.50 cm., loss tangent = 0.0006). α_c is the corresponding dominant H-mode attenuation in conventional parallel-plate waveguide (a = 6.89 cm.).

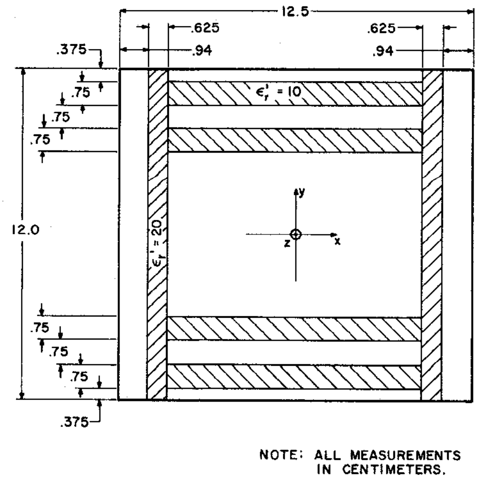

Fig. 5 - Cross-section of rectangular reactive-wall waveguide used in experimental verification of the theoretical analysis.

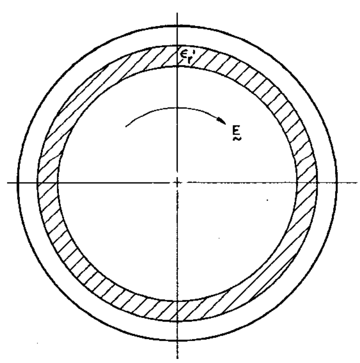

Fig. 6 - Reactive-wall waveguide of circular cross-section, operating in the H_{01} mode.