Dispersion Characteristics of Substrate Integrated Rectangular Waveguide

Y. Cassivi, L. Perregrini, P. Arcioni, M. Bressan, K. Wu, and G. Conciauro

***Abstract*—Dispersion properties of the substrate integrated rectangular waveguide (SIRW) are rigorously obtained using the BI-RME method combined with the Floquet's theorem. Our analysis shows that the SIRW basically has the same guided-wave characteristics as the conventional rectangular waveguide. Empirical equations are derived from the calculated dispersion curves in order to estimate the cutoff frequency of the first two dominant modes of the SIRW. To validate the analysis results, an SIRW guide was designed and measured. Very good agreements between the experimental and theoretical results were obtained.**

***Index Terms*—Integrated waveguide, millimeter-wave.**

I. Introduction

THE substrate integrated rectangular waveguide or SIRW, as shown in Fig. 1(a), which was recently introduced [1], [2], is useful for the design of millimeter-wave circuits such as filters, resonators, and antennas. Also, it can easily be connected to microstrip or coplanar circuit using simple transitions [1], [2]. The SIRW together with other types of synthesized waveguide can be generalized by a new concept called "substrate integrated circuits (SICs)" that allows the integration of planar and nonplanar structures within the same substrate [3]. So far, this type of structure was simulated with three–dimensional (3-D) finite element method (FEM) programs [2], [4] and with Galerkin method of moment [5], but no information was given on guided-wave properties of such a guide.

In this letter, the generalized admittance matrix of a periodic cell [Fig. 1(a)] of the SIRW is calculated using the BI-RME method [6]. This method was recently extended to the computation of the generalized admittance matrix of waveguide structures that can involve any form of metallized posts near the physical ports [7]. This method can be used for the analysis of the SIRW, which is a laterally open structure [Fig. 1(b)], by placing it within a closed waveguide as illustrated in Fig. 1(c). The effect of the added enclosure is negligible if the electromagnetic field is well confined inside the SIRW, which is the case for a practical SIRW having a minimum lateral radiation loss level.

Because of the periodicity, the Floquet's theorem can be used to obtain an eigenvalue system. The eigenvalues yield guided-wave properties of the propagating modes of the SIRW and the eigenvectors provide the pattern of the modal fields. From the analysis, approximate equations are given to predict cutoff frequency of the first and second propagating modes of the SIRW.

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II. Description of the Method

The calculation of the admittance matrix of a periodic cell involving metallized posts placed in a dielectric substrate electrically bounded on both lateral and top/bottom sides, as illustrated in Fig. 1(c), is carried out by the BI-RME method [7]. Let us consider N TE_{n0} modes on each physical port. The formulation of the admittance matrix of the circuit can then be written by the following equation

$$Y_{ij}^{(sr)} = \frac{A_{ij}^{(sr)}}{j\omega} + j\omega B_{ij}^{(sr)} + j\omega^3 \sum_{p=1}^{P} \frac{C_{ip}^{(s)} C_{jp}^{(r)}}{\omega_p^2(\omega_p^2 - \omega^2)} \qquad (1)$$

where $i, j = 1, 2$ refer to the input or output physical ports, $s, r = 1, \ldots, N$ refer to the modes on ports i, j, respectively, and P is the number of resonances of the short-circuited structure taken into account in the BI-RME modeling. The quantities $A_{ij}^{(sr)}, B_{ij}^{(sr)}, C_{ip}^{(s)}$, and ω_p are frequency independent and are calculated very efficiently by the BI-RME method [6]. From the admittance matrix, the chain matrix can be generated as follows

$$\begin{bmatrix} ABCD_{11} & ABCD_{12} \\ ABCD_{21} & ABCD_{22} \end{bmatrix} = \begin{bmatrix} -Y_{21}^{-1} \cdot Y_{22} & -Y_{21}^{-1} \\ Y_{12} - Y_{11} \cdot Y_{21}^{-1} \cdot Y_{22} & -Y_{11} \cdot Y_{21}^{-1} \end{bmatrix}$$

where $\mathbf{Y}_{11}, \mathbf{Y}_{12}, \mathbf{Y}_{21}$, and $\mathbf{Y}_{22}$ are the four submatrices of the admittance matrix. Applying the Floquet's theorem, we obtain the following eigenvalue system:

$$\begin{bmatrix} ABCD_{11} & ABCD_{12} \\ ABCD_{21} & ABCD_{22} \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} = e^{\gamma b} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \qquad (2)$$

The resulting eigenvalues give the propagation constants γ of the SIRW modes, whereas the eigenvectors are the weight coefficients that give the SIRW modal fields in terms of TE_{n0} modes of the physical port (i.e., the Fourier expansion of the SIRW modes). The visual inspection of these modal fields permits the identification of the modes capable of propagating in a laterally open SIRW.

Since the wideband calculation of the Y-matrix by using (1) requires only one electromagnetic analysis of the structure, we can easily calculate the chain matrix at many frequency points and from (2) obtain a high resolution of the dispersion curves within negligible time.

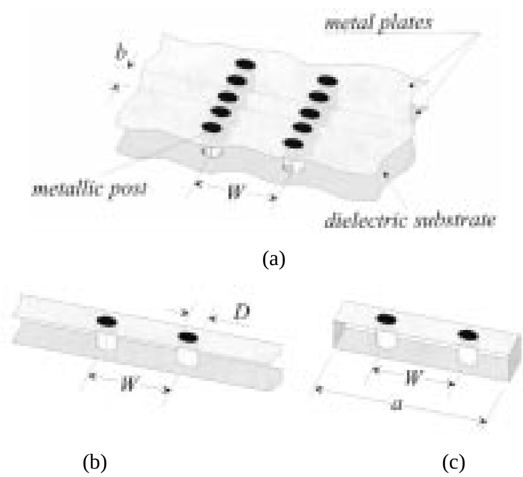

Fig. 1. Topology of the SIRW and identification of the periodic cell: (a) 3-D representation of the SIRW; (b) transversal view of an ideal SIRW with infinite width; (c) transversal view of the SIRW to be studied that is enclosed in a fictitious rectangular waveguide.

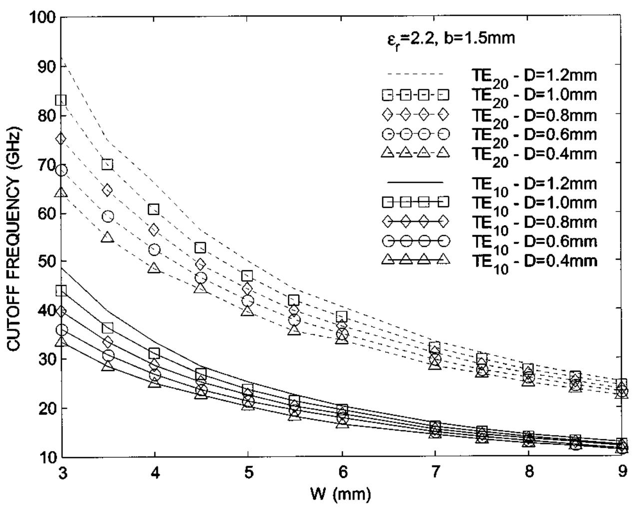

Fig. 2. Cutoff frequencies of the TE_{10}-like and TE_{20}-like modes of the straight pattern SIRW versus W and D.

III. Analysis of Structure

Using the method as described above, the correspondence between the cutoff frequencies of the TE_{10}-like and TE_{20}-like modes of the SIRW, with respect to the diameter D and the spacing W of the metallized holes is evaluated. Fig. 2 presents calculated results for the cutoff frequencies of the TE_{10} and TE_{20} modes of the SIRW. These curves can be approximated by the following relations, which were obtained by a least square approach:

$$F_{C(\mathrm{TE}_{10})} = \frac{c_O}{2\cdot\sqrt{\varepsilon_R}}\cdot\left(W - \frac{D^2}{0.95\cdot b}\right)^{-1} \quad (3)$$

$$F_{C(\mathrm{TE}_{20})} = \frac{c_O}{\sqrt{\varepsilon_R}}\left(W - \frac{D^2}{1.1\cdot b} - \frac{D^3}{6.6\cdot b^2}\right)^{-1} \quad (4)$$

where c_0 is the speed of light in free space. Note that (3) and (4) do not depend on the thickness of the waveguide. The thickness will only affect the Q-factor [2]. The precision of (3) is within

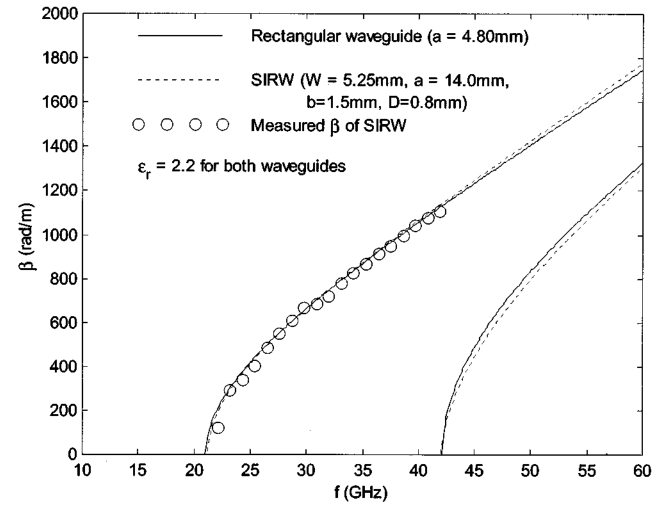

Fig. 3. Comparison of the dispersion curves of an SIRW with an equivalent rectangular waveguide.

$\pm 5\%$. For (4), a precision better than $+4\%/-9\%$ is possible. These approximations are valid for $b < \lambda_o\cdot\sqrt{\varepsilon_r}/2$ and $b < 4D$.

IV. Experimental Results

To verify the accuracy of our method, several SIRW guides were constructed. The propagation constant is extracted by measuring the phase difference of two guides of different length. It is interesting to compare the dispersion curves of the first two modes of the SIRW with those of an equivalent rectangular waveguide filled with the same dielectric material. Fig. 3 presents the simulation results for both modes plus the measurement results for the first mode of the SIRW. These results indicate that both types of waveguide practically have the same dispersion characteristics. Therefore, the SIRW is equivalent to a rectangular waveguide and it can be analyzed as a rectangular waveguide just by using the effective width W_{eff} of the SIRW. It can be derived from (3), as follows

$$W_{\mathrm{eff}} = W - \frac{D^2}{0.95\cdot b} \quad (5)$$

provided that the spacing between the posts is sufficiently small.

V. Conclusion

We have presented the use of a generalized BI-RME method for obtaining the propagation characteristics of an SIRW. This approach has been validated experimentally. We have demonstrated that the guided-wave characteristics of the SIRW are equivalent to those of a rectangular waveguide with an equivalent width.

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