From Figs. 10–12, we come to the following conclusions. For the odd mode, when b becomes larger, the equivalent length of the resonator becomes shorter and, hence, the curve of its input susceptance shifts to the higher frequency region. On the other hand, since two resonators are always in the same electric potential for the even mode, varying b never changes its input susceptance. Therefore, when b becomes larger, the intersections between the curves of the input susceptance of both modes, i.e., the attenuation pole frequencies, move toward the higher frequency region. In this case, the attenuation pole around 4 GHz is most sensitive because the input susceptance of the odd mode shows the largest change for varying b.

Consequently, it is reasonable to tell that the attenuation-pole frequencies can be regulated by changing the position of the metal pin, which connects two resonators.

IV. Conclusions

In this paper, we have proposed a dual-plane comb-line filter having plural attenuation poles. The filtering characteristics have been investigated from both experiments and numerical simulations by means of the FD-TD method. It has been shown that this filter has attenuation poles just above, as well as below the passband, and that this feature makes the filter response preferably sharp. It has also been shown that intersections between the curves of the input susceptance of the even and odd modes agree with the attenuation-pole frequencies. Furthermore, it has been demonstrated that, by changing the position of the metal pin, which connects two resonators, we can change the input susceptance of the odd mode alone and, hence, regulate the attenuation-pole frequencies.

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A New Hybrid Mode-Matching/Numerical Method for the Analysis of Arbitrarily Shaped Inductive Obstacles and Discontinuities in Rectangular Waveguides

H. Esteban, S. Cogollos, V. E. Boria, A. San Blas, and M. Ferrando

***Abstract*—A new and efficient hybrid mode-matching method is presented for the analysis of arbitrarily shaped inductive obstacles and/or discontinuities in a rectangular waveguide. The irregular region with obstacles and/or discontinuities is characterized using a full-wave hybrid spectral/numerical open-space technique expanding the fields in cylindrical wave functions. Next, a full-wave mode-matching procedure is used to match the cylindrical wave functions to guided modes in all ports and a generalized scattering matrix for the structure is finally obtained. The obstacles can be metallic or dielectric with complex permittivities and arbitrary geometries. The structure presents an arbitrary number of ports, each one with different orientation and dimensions. The accuracy of the method is validated comparing with results for several complex problems found in the literature. CPU times are also included to show the efficiency of the new method proposed.**

***Index Terms*—Microwave devices, mode-matching methods, spectral analysis, waveguide discontinuities.**

I. Introduction

Inductive obstacles and discontinuities in waveguiding structures have traditionally been a key element of many microwave devices, such as bandpass [1], [2] and band-stop [3] filters, post-coupled filters [3], [4], tapers [5], phase shifters [6], circulator elements [7], [8], rounded-corners effect [9], mitered bends [7], [10], [11], or manifold diplexers and multiplexers [12]. The correct analysis and design of these microwave devices is of great importance for many applications such as satellite and wireless communication systems [13]. Therefore, the analysis of inductive obstacles and discontinuities has recently received considerable attention in the technical literature [9], [11].

The existing methods for the analysis of the microwave devices just mentioned before fall into one of the three following categories:

1) analytical methods;
2) numerical methods;
3) hybrid methods.

The analytical or modal methods, such as those based on the generalized admittance matrix (GAM) method [14] or generalized scattering matrix (GSM) method [15], provide accurate and efficient results, but are only applicable to a few regularly shaped waveguide problems. On the other hand, the numerical or space discretization methods, such as the finite-element (FE) method [16], [17] or finite-difference time-domain (FDTD) method [18], are able to analyze problems with arbitrary geometries, but suffer from huge CPU time and storage requirements. An alternative to analytical and numerical methods is the combination of the main advantages of both types of techniques: the efficiency of modal methods and the flexibility of numerical methods. This is the aim of the so-called hybrid methods, which combine numerical and analytical techniques for the efficient analysis of a wide range of problems. A great number of hybrid techniques have been reported over the last years, with an increasing degree of flexibility. A combination of the moments method and the mode-matching technique

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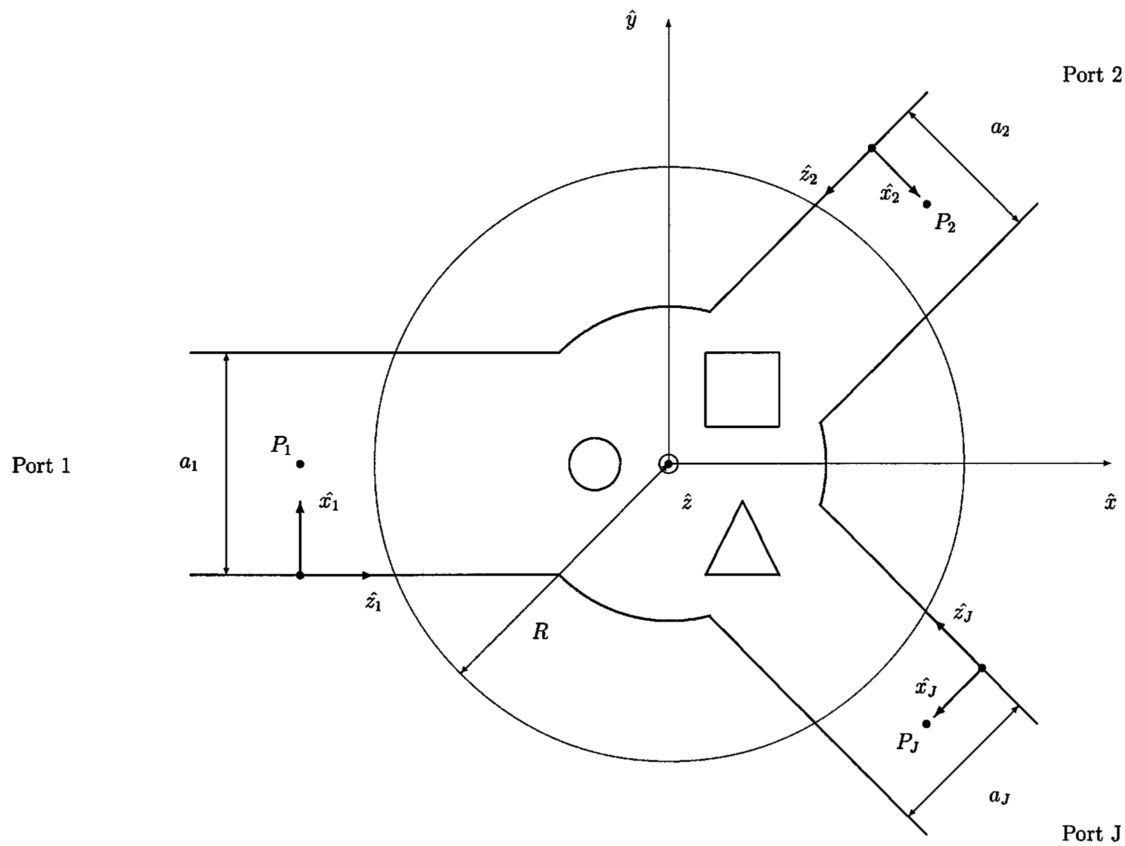


Fig. 1. Geometry of an arbitrary inductive problem in rectangular waveguide.

is presented in [2], [19], and [20], where a single dielectric or metallic post problem in a rectangular waveguide is analyzed. In [21], a method for the analysis of multiple dielectric or metallic obstacles with arbitrary shape is presented. However, this method needs the translation of GAM matrices to GSM matrices, which may result in singularities. Furthermore, it cannot cope with discontinuity problems. A boundary contour mode-matching method (BCMM) has been recently published [7], which is able to analyze multiple port discontinuities with arbitrary shape, including the presence of a circular metallic post. More recently, a new BCMM has been presented in [22], which analyzes rectangular waveguides with multiple arbitrarily shaped metallic posts, but does not simultaneously analyze the presence of multiple ports and discontinuities. The BCMM presented in [7] has been extended in [11] to an analytical method (avoiding the numerical integration of the former method). The increase in efficiency and accuracy has, however, resulted in a decrease in the flexibility of the method, which analyzes the same multiple port discontinuity problem, but does not include the presence of a metallic post.

In this paper, a new hybrid method based on the moments method and the mode-matching procedure is presented. This new method is able to analyze any inductive problem in a rectangular waveguide. An arbitrarily shaped inductive region (see Fig. 1) is considered, where there is any number of ports accessing an arbitrarily shaped region containing any number of metallic, dielectric, or lossy dielectric obstacles of arbitrary shape. The analysis is performed combining a hybrid formulation with segmentation. Thus, the scattering problem is split into small individual scatterers, and each scatterer is characterized individually, using the analytical solution where possible (i.e., the well-known solution described in [23] for a circular cylinder), and the numerical moments method for the noncanonical objects. The coupling among scatterers is solved using the iterative spectral method already presented in [24], and the mode-matching procedure is finally employed to match cylindrical wave functions (used to characterize the scatterers) to the external guided modes of the accessing ports. The integrations needed to perform the mode-matching procedure are reduced to a simple matrix multiplication. The new method is, therefore, suitable for the analysis of a wide range of waveguiding problems (all inductive geometries with TE_{m0} incidence), and it is highly efficient compared to numerical methods because the only part of the method that is numerically solved is the characterization of some noncanonical two-dimensional (2-D) individual scatterers.

In Section II, the new hybrid method is briefly outlined. In Section III, the hybrid method is validated comparing its results with those previously reported in the literature. Finally, Section IV includes some conclusions of the method proposed, and possible extensions are discussed.

II. Theory

The general layout of the problem is depicted in Fig. 1. An irregular waveguide segment, invariant in the z dimension, is illustrated. An arbitrary number (J) of rectangular waveguide access ports is considered. Within this segment, several arbitrarily shaped obstacles can exist. Let a_i $(i \in [1, \ldots, J])$ be the width of port i. The position and tilt of each port is defined by the point P_i and the unit vectors $\hat{x}_i$ and $\hat{z}_i$ $(i \in [1, \ldots, J])$. A global coordinate system is defined by unit vectors $\hat{x}$, $\hat{y}$, and $\hat{z}$ (see Fig. 1). As the geometry of the whole structure is invariant in the z dimension, only coordinates (x, y) or (ρ, ϕ) are considered in the global coordinate system. The irregular segment is enclosed by a circumference of radius R.

The guided waves that are incident to the segment are TE_{m0} modes. As the segment is invariant in the z-direction, the reflected and transmitted waves are also TE_{m0} modes, which means that all the electric fields are polarized in the z-direction.

Therefore, the irregular segment can be characterized using the radial-mode-expansion method described in [24]. This method provides a transfer function $\underline{\underline{D}}$, which relates the incident and scattered electric field spectra as follows:

$$[c_q] = \underline{\underline{D}} \cdot [i_p] \rightarrow c_q = \sum_{p=-N_{\rm in}}^{N_{\rm in}} D_{qp} i_p \tag{1}$$

where i_p is the cylindrical spectrum of the incident electric field and c_q is the spectrum of the scattered electric field. For computational reasons, both spectra have been truncated to a finite number of terms, as shown in the following expressions:

$$\vec{E}^{\rm in}(\rho, \phi) = \sum_{p=-N_{\rm in}}^{N_{\rm in}} i_p J_p(K\rho) e^{jp\phi} \hat{z} \tag{2}$$

$$\vec{E}^{\rm sc}(\rho, \phi) = \sum_{q=-N_{\rm sc}}^{N_{\rm sc}} c_q H_q^{(2)}(K\rho) e^{jq\phi} \hat{z} \tag{3}$$

where $N_{\rm in}$ must be large enough to correctly reconstruct the incident field inside the circumference that contains the segment, and $N_{\rm sc}$ must satisfy $N_{\rm sc} > KR$, R being the radius of the circumference that contains the segment. In order to simplify the notation, it is convenient to extend the series in (2) and (3) to the same number of terms $N = \max(N_{\rm in}, N_{\rm sc})$, thus producing a square $\underline{\underline{D}}$ matrix. It can be simply proven that the value of N required for an accurate reconstruction of the incident and scattered field must satisfy the following condition:

$$N \geq \max\left(\frac{M_i \pi R}{a_i} + 3\frac{\pi}{a \sin\left(\frac{a_i}{2R}\right)}, KR\right), \qquad i \in [1, \ldots, J]. \tag{4}$$

Once the matrix $\underline{\underline{D}}$ is computed, the irregular segment with all the inductive obstacles and discontinuities is characterized using cylindrical mode functions. In order to characterize the segment in terms of guided waves, standard rectangular waveguide modes should be matched to cylindrical open-space modes. This can be accomplished by enforcing the continuity of transversal electrical and magnetic fields in the circumference of radius R that encloses the segment

$$\vec{E}_t^{\rm in}(\rho = R, \phi) + \vec{E}_t^{\rm sc}(\rho = R, \phi) = \vec{E}_t^{\rm wg}(\rho = R, \phi) \tag{5}$$

$$\vec{H}_t^{\rm in}(\rho = R, \phi) + \vec{H}_t^{\rm sc}(\rho = R, \phi) = \vec{H}_t^{\rm wg}(\rho = R, \phi) \tag{6}$$

where $\vec{E}_t^{\rm wg}$ and $\vec{H}_t^{\rm wg}$ are the electric and magnetic transversal fields in the waveguide access ports, which can be expressed as the following summations:

$$\vec{E}_t^{\rm wg}(R, \phi) = \sum_{i=1}^{J} \vec{E}_t^i(R, \phi) = \sum_{m=1}^{M} \left[a_m e_m^+(\phi) + b_m e_m^-(\phi)\right] \hat{z} \tag{7}$$

$$\vec{H}_t^{\rm wg}(R, \phi) = \sum_{i=1}^{J} \vec{H}_t^i(R, \phi) = \sum_{m=1}^{M} \left[-a_m Y_{\mathrm{TE}_{m0}} e_m^+(\phi) + b_m Y_{\mathrm{TE}_{m0}} e_m^-(\phi)\right] \hat{t}. \tag{8}$$

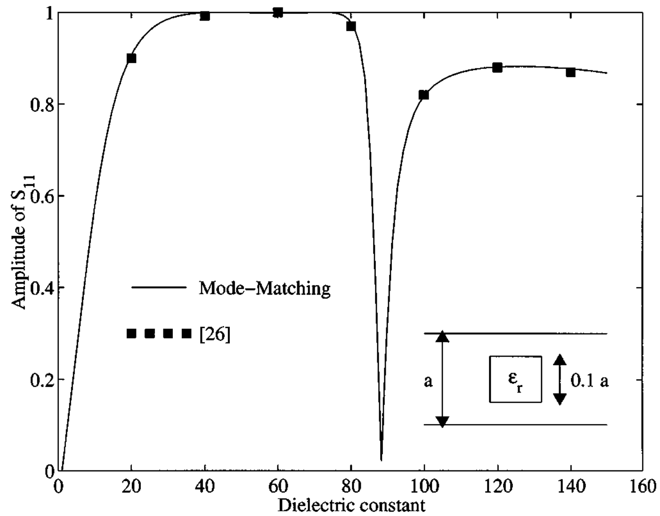


Fig. 2. Variation of $|S_{11}|$ with the dielectric constant for a centered dielectric square post ($f_c/f = 0.7$).

In these expressions, $e_m^+(\phi)$ and $e_m^-(\phi)$ are the vector mode functions of the mth incident and reflected guided modes including the exponential term. These vector mode functions, together with their characteristic admittance $(Y_{\mathrm{TE}_{m0}})$, are explicitly defined in [25]. The unit vector $\hat{t}$ in (8) defines a transversal direction, which is used to project the magnetic fields and enforce continuity.

Applying a mode-matching technique to (5) and (6), a matrix system is finally obtained. The solution of this matrix system provides the GSM of the guided structure $(\underline{\underline{S}})$

$$\underline{\underline{\Delta}}\,\underline{\underline{S}} = \underline{\underline{Q}} \rightarrow \underline{\underline{S}} = \underline{\underline{\Delta}}^{-1}\underline{\underline{Q}} \tag{9}$$

where $\underline{\underline{\Delta}}$ and $\underline{\underline{Q}}$ are matrices whose elements are the following integral expressions along the circumference of radius R:

$$\Delta_{mn} = \frac{1}{2\pi}\int_0^{2\pi}\left[Y_{\mathrm{TE}_{n0}} e_n^-(\phi) - \frac{j}{K\eta R}\frac{\mathrm{d}e_n^-}{\mathrm{d}\phi}(\hat{\rho}\cdot\hat{t}) + \frac{j}{\eta}\sum_{q=-N}^{N} w_q(\phi) E_{qn}^-(\hat{\phi}\cdot\hat{t})\right] e_m^-(\phi)^* \mathrm{d}\phi \tag{10}$$

$$Q_{mn} = \frac{1}{2\pi}\int_0^{2\pi}\left[Y_{\mathrm{TE}_{n0}} e_n^+(\phi) + \frac{j}{K\eta R}\frac{\mathrm{d}e_n^+}{\mathrm{d}\phi}(\hat{\rho}\cdot\hat{t}) - \frac{j}{\eta}\sum_{q=-N}^{N} w_q(\phi) E_{qn}^+(\hat{\phi}\cdot\hat{t})\right] e_m^-(\phi)^* \mathrm{d}\phi \tag{11}$$

where $E_{qn}^{\pm}$ is the inverse discrete time Fourier transform (DTFT) of $e_n^{\pm}(\phi)$ as follows:

$$E_{qn}^{\pm} = \frac{1}{2\pi}\int_{-\pi}^{\pi} e_n^{\pm}(\phi) e^{-jq\phi} \mathrm{d}\phi \tag{12}$$

and $w_q(\phi)$ is the direct DTFT of W_{qp} as follows:

$$w_q(\phi) = \sum_{p=-\infty}^{\infty} W_{qp} e^{jp\phi}. \tag{13}$$

The W_{qp} coefficients are the elements of the following matrix $\underline{\underline{W}}$:

$$\underline{\underline{W}} = \left(\underline{\underline{J'}} + \underline{\underline{H'}}\,\underline{\underline{D}}\right)\left(\underline{\underline{J}} + \underline{\underline{H}}\,\underline{\underline{D}}\right)^{-1} \tag{14}$$

where $\underline{\underline{J}}$, $\underline{\underline{H}}$, $\underline{\underline{J'}}$, and $\underline{\underline{H'}}$ are diagonal matrices whose elements are the Bessel and Hankel functions, and their derivatives, evaluated at KR.

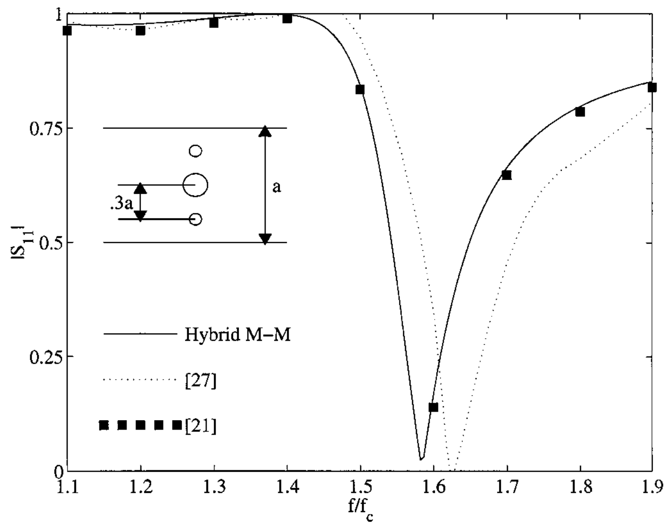


Fig. 3. Variation of $|S_{11}|$ with frequency for a symmetric triple-post configuration ($\varepsilon_r = 38.0$).

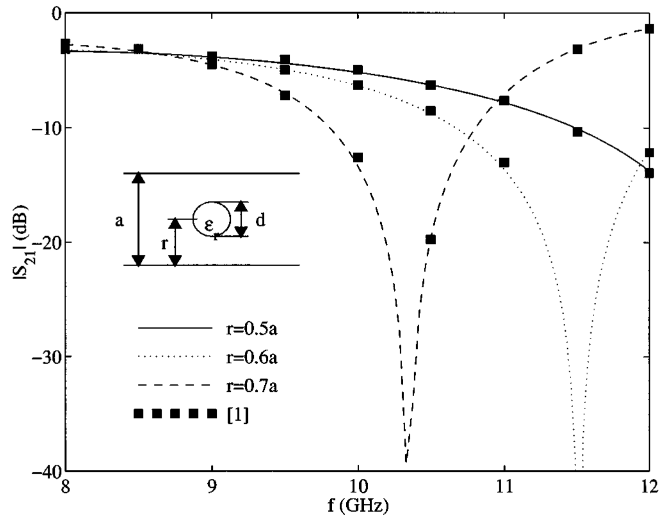


Fig. 4. Frequency response ($|S_{21}|$) for a band-stop filter ($\varepsilon_r = 38.5$, $\tan\delta = 2 \times 10^{-4}$, $d = 0.03a$, $a = 22.86$ mm).

According to (10) and (11), the evaluation of Δ_{mn} and Q_{mn} elements requires the computation of integrals of products of 2–3 functions along the circumference of radius R. Making use of the DTFT, the solution of these integrals can be analytically computed through the following matrix product, thus avoiding a high CPU time-consuming numerical computation

$$\underline{\underline{\Delta}} = \left[\underline{\underline{E}}^-\right]^+ \left[\underline{\underline{E}}^- \underline{\underline{Y_{\mathrm{TE}}}} + \left(\frac{1}{K\eta R}\underline{\underline{\Gamma}}^T \underline{\underline{P}} + \frac{j}{\eta}\underline{\underline{\Phi}}^T \underline{\underline{W}}\right) \underline{\underline{E}}^-\right] \quad (15)$$

$$\underline{\underline{Q}} = \left[\underline{\underline{E}}^-\right]^+ \left[\underline{\underline{E}}^+ \underline{\underline{Y_{\mathrm{TE}}}} - \left(\frac{1}{K\eta R}\underline{\underline{\Gamma}}^T \underline{\underline{P}} + \frac{j}{\eta}\underline{\underline{\Phi}}^T \underline{\underline{W}}\right) \underline{\underline{E}}^+\right] \quad (16)$$

where $\underline{\underline{E}}^{\pm}$ and $\underline{\underline{Y_{\mathrm{TE}}}}$ are matrices whose elements are, respectively, $E_{qn}^{\pm}$ and $Y_{\mathrm{TE}_{m0}}$. $\underline{\underline{P}}$ is a diagonal matrix whose elements are $[-N, \ldots, N]$. Finally, $\underline{\underline{\Gamma}}$ and $\underline{\underline{\Phi}}$ are Toeplitz matrices with the elements of the first row defined as follows:

$$\Gamma_n = \frac{1}{2\pi}\int_{-\pi}^{\pi} (\hat{\rho} \cdot \hat{t}) e^{-jn\phi} \mathrm{d}\phi \quad (17)$$

$$\Phi_n = \frac{1}{2\pi}\int_{-\pi}^{\pi} (\hat{\phi} \cdot \hat{t}) e^{-jn\phi} \mathrm{d}\phi. \quad (18)$$

III. Results and Discussion

In this section, the new hybrid mode-matching method has been used to analyze some inductive problems in order to validate its accuracy and efficiency. The analysis of arbitrarily shaped inductive obstacles in a rectangular waveguide is first validated (cylindric and square dielectric posts). Next, results are presented for two inductive discontinuity problems (a circular bend and a compensated T-junction). Finally, the analysis of a complex H-plane waveguide device, such as a multiple (metallic and dielectric) post filter, is successfully performed.

A. Inductive Obstacles

The validity of the method for the analysis of arbitrarily shaped inductive obstacles in a rectangular waveguide is shown in Fig. 2, where the reflection coefficient ($|S_{11}|$) of a waveguide with a square dielectric post is shown. The reflection coefficient has been computed varying the dielectric constant, and results are in good agreement with the literature [26].

Multiple obstacle problems have also been analyzed with the hybrid mode-matching method. The scattering of a waveguide with three circular dielectric posts ($\varepsilon_r = 38.0$) is shown in Fig. 3. Results do not agree very well with those of Hsu and Auda [27]. In their analysis, as pointed in [26], Hsu and Auda have discretized circular contours with

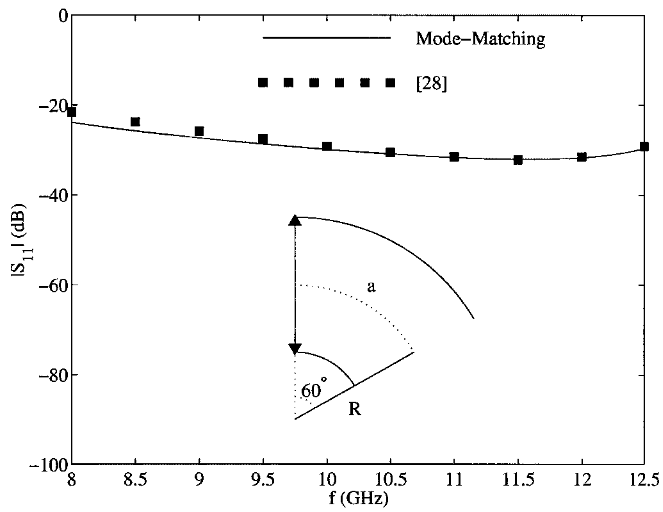


Fig. 5. 60° circular bend ($a = 22.9$ mm, $R = 0.384a$).

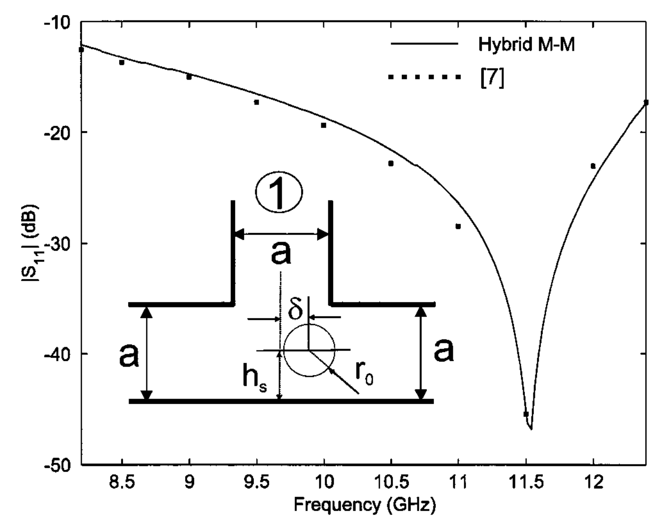
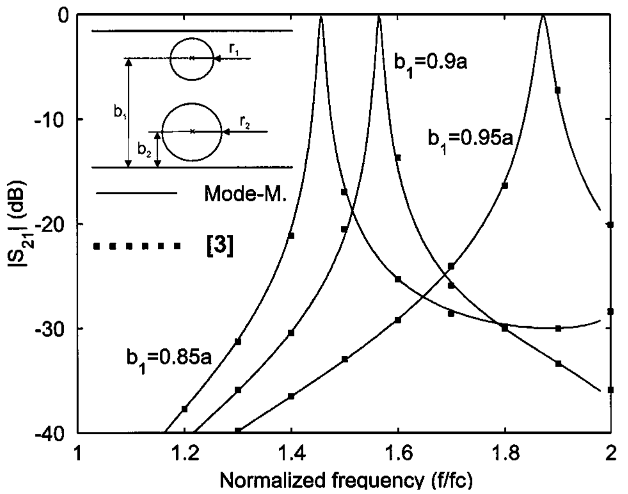
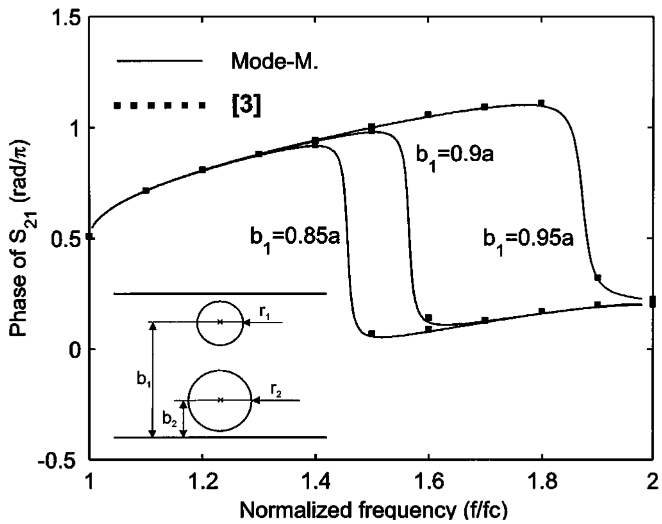


Fig. 6. H-plane T-junction with a circular post.



(a)



(b)

Fig. 7. Frequency response of a tunable bandpass filter with one dielectric and one metallic post. (a) Amplitude of the transmission coefficient. (b) Phase of the transmission coefficient.

triangular simplexes. This may introduce slight errors, which would add up in configurations with several cylinders. Moreover, results presented in [21] for the same problem are in good agreement with results from the hybrid mode-matching method (see Fig. 3), and also differ from results of the Hsu and Auda contribution.

A band-stop filter composed of a waveguide with a lossy dielectric circular post (complex permittivity) has also been simulated to prove the validity of the method with lossy materials. Results are shown in Fig. 4 for $a = 22.86$ mm, $\varepsilon_r = 38.5$, $\tan\delta = 2 \times 10^{-4}$, and $d = 0.03a$. The response of the filter is given for three different positions of the post ($r = 0.5a$, $r = 0.6a$, and $r = 0.7a$) and compared to results from Geshe and Lochel [1], showing very good agreement.

In the analysis of the previous inductive obstacle problems, the computation time for each frequency point was around 0.5 s with a Pentium 400-MHz processor, and very few guided modes (between 3–5) were necessary in each accessing port to obtain convergent results.

B. Inductive Discontinuities

The validity of the hybrid mode-matching method for the analysis of inductive discontinuities of arbitrary shape is demonstrated in the following results. In Fig. 5, the reflection coefficient of a 60° circular bend ($a = 22.9$ mm, $R = 0.384a$) is illustrated, and validated with results from [28]. In Fig. 6, an H-plane T-junction with a cylindrical post is analyzed. The reflection coefficient is illustrated and compared with results from [7].

The number of guided modes (3–5, depending on the geometry), and the computational time required for the analysis of inductive discontinuities (around 0.5 s) were similar to those in the analysis of inductive obstacles.

C. H-Plane Components and Devices

A final result is presented to prove the validity of the hybrid mode-matching method for the analysis of complex inductive structures. In Fig. 7, the frequency response of the transmission coefficient of a tunable bandpass filter with one small dielectric post and one large metallic post is shown. The dielectric post is made of a ceramic material of complex permittivity ($\varepsilon_r = 38.5$ and $\tan\delta = 2 \times 10^{-4}$) and radius $r_1 = 0.03h$, with h being the width of the waveguide. The metallic post is a large one, of radius $r_2 = 0.3h$, and placed touching one of the plates of the waveguide ($b_2 = 0.3h = r_2$). The transmission coefficient (amplitude and phase) is shown in Fig. 7 for various positions of the dielectric post ($b_1 = 0.85h$, $b_1 = 0.9h$, and $b_1 = 0.95h$). Results are successfully compared with those of [3].

IV. Conclusions

A new method has been presented in this paper for the analysis of inductive problems in a rectangular waveguide. The method has proven to be accurate and efficient, and it can solve a wide range of problems in a rectangular waveguide: inductive metallic or dielectric (complex permittivity) obstacles of arbitrary geometry, and/or inductive discontinuities of any shape, with multiple ports accessing an irregular waveguide segment. The method described in this paper is a hybrid method since it combines the numerical method of moments for the analysis of arbitrarily shaped scatterers with a spectral modal technique for the analysis of the coupling among objects. Finally, a mode-matching procedure is used to match open-space modes to the modes in the accessing waveguide ports. The hybrid mode-matching method has been validated with results for several inductive problems previously reported in the literature.

A future line of research in this field is the inclusion of the method in a computer-aided design (CAD) tool for the design of microwave devices of practical interest such as filters, diplexers, multiplexers, etc. Another future line of research is the extension of the method, first to the analysis of capacitive problems (i.e., capacitive steps and obstacles and, in general, E-plane structures), and next to the analysis of completely three-dimensional (3-D) structures such as tuning screws in waveguide filters.

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A Balanced FET FMCW Radar Transceiver With Improved AM Noise Performance

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***Abstract*—A balanced FET frequency-modulated continuous-wave radar transceiver designed to suppress AM noise is presented. The transceiver utilizes the same device for output power amplification as for down-conversion of the received signal, thereby avoiding the need for separation of these signals. This makes the transceiver suitable for integration in monolithic-microwave integrated-circuit technology. A test circuit operating at 10 GHz was designed. The AM noise suppression is characterized, as well as output power and noise performance. Comparison with an unbalanced transceiver using the same principle of operation shows an improvement of 20 dB in AM noise performance. The output power is 14 dBm at 7-dBm input power.**

***Index Terms*—AM noise, FMCW, radar, transceiver.**

I. Introduction

The use of frequency-modulated continuous-wave (FMCW) radars for different high-volume applications, such as automotive collision avoidance, cruise control, and fluid-level indicators has increased in recent years. Several approaches to the design of the transceivers used for those radars have been presented [1]–[3].

Recently, the authors presented a novel FET transceiver suitable for FMCW radar applications [4]. The transceiver utilizes a single FET to simultaneously amplify the transmitted signal, and as a resistive mixer, to down-convert the received signal, making it suitable for integration in monolithic-microwave integrated-circuit (MMIC) technology.

One major limitation of the performance of FMCW radars comes from noise in the transmitter oscillator being down-converted to baseband in the receiver. This can limit the dynamic range of the radar and, thus, decrease the resolution.

AM noise from the transmitter oscillator can significantly contribute to the IF noise in the receiver [5], and should, if possible, be suppressed. Different methods to suppress AM noise in FMCW transceivers have been reported [6], [7]. Most of them utilize balanced topologies.

For short-range radars, the received and transmitted signals are strongly correlated. In most short-range FMCW radars, the same oscillator is used for the transmitter and receiver mixer. The oscillator FM noise will then cancel in the down-conversion of the received signal [5], [6]. For short-range radars, AM noise is, therefore, generally more severe than FM noise.

In this paper, we present a balanced design of the unbalanced FET transceiver [4] with improved capability of AM noise suppression in FMCW radar applications.

II. Balanced Circuit Topology

When analyzing the FET transceiver, it can be considered as a FET resistive mixer with the input signal (IN) serving as a local oscillator (LO) and the LO to RF leakage providing the transmitted signal

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