Computer-Aided Design and Optimization of NRD-Guide Mode Suppressors

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***Abstract*— A novel class of optimized nonradiative dielectric waveguide (NRD-guide) mode suppressors are proposed for wide-band applications in passive and active NRD integrated circuits. A rigorous field-theoretical analysis is made by using the frequency-domain TLM technique. The optimum design is based on a filter-like scheme with a low-pass filter simulation technique and its performance-prediction algorithm. Compared to the existing choke metallic pattern, the proposed mode suppressor demonstrates excellent capabilities of effectively suppressing unwanted modes while offering a more compact geometry. Using the geometry proposed in this work for a three-section low-pass filter, for example, it is found that the transmission loss of the mode suppressor is better than −30 dB over the frequency band of interest which is well confirmed theoretically and experimentally. In addition, the length of the resulting mode suppressor becomes shorter than its counterpart using the choke metallic pattern by 20%. The theoretical prediction of electrical performance is well confirmed by our measurements.**

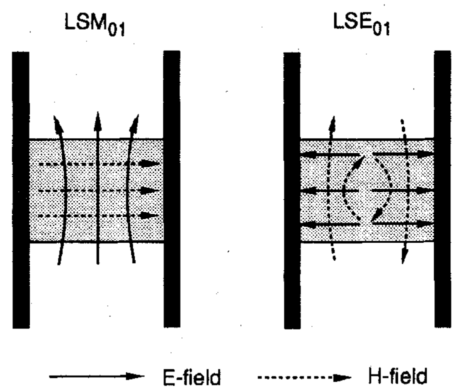

Fig. 1. Field profiles of two fundamental modes in NRD-guide.

I. Introduction

NONRADIATIVE dielectric waveguide (NRD-guide) [1] was proposed for millimeter-wave applications because of its simplicity, ease of fabrication and low-loss nature. Moreover, radiation at curved sections and discontinuities is nearly nonexistent. A number of passive and active circuits based this technology have demonstrated its superiority over other millimeter-wave structures in the band of 20–150 GHz [2]. Note that most of design techniques used for the NRD-guide components were empirical and approximate. Due to the dispersive nature of the NRD geometry, efficient and accurate electromagnetic modeling has to be considered for successful computer-aided design of various NRD circuits.

One of the key issues in successful applications of the NRD-guide technology is how to suppress effectively or at least diminish the propagation of unwanted modes. This is really a complex problem because mode propagation and the mode spectrum of NRD-guide may lead to coupled-mode effects or mode-degenerating problems. Generally speaking, modes of an NRD-guide are usually classified into LSM and LSE modes according to its geometry. The field profiles of the lowest LSM mode (LSM_{01}) and LSE mode (LSE_{01}) are shown in Fig. 1. Since the LSM_{01} is selected as the operating mode of the NRD-guide due to its lower transmission loss, the LSE_{01} mode, which has a lower cut-off frequency than the wanted operating mode, needs to be suppressed. Of course, the LSE_{01} mode can be also used for coupling LSM01 mode from one branch of the NRD-guide to another for power divider applications. In most cases, however, it is undesirable to have any LSE_{01} mode propagation since it may strongly affect high-quality propagation of the LSM_{01}. To this end, a mode suppressing technique has been proposed and used to suppress the unwanted LSE_{01} mode [3]. The mode suppressor becomes a key element in successful applications of the NRD-guide technology. In the solution that has been proposed in [3], the metal strip is inserted in the H-plane, perpendicular to the metallic wall of the NRD-guide. In this way, the LSE_{01} mode can be, in principle, eliminated without affecting the LSM_{01} mode propagation owing to the orthogonality of the two modes in space. However, such an arrangement may cause problems; the resulting gaps between the mode suppressor and the metallic walls generate unwanted mode conversion from the LSE_{01} mode to TEM mode. This is because under such a situation the whole structure can be regarded as a suspended sandwiched microstrip line, along which the TEM mode will propagate. Hence, a $\lambda/4$ choke pattern has been suggested [3] for suppressing the TEM mode. It has been reported that the parasitic mode, for instance, can be suppressed below −20 dB by means of a five-stage mode suppressor.

This paper presents a class of new mode suppressors which can be called the filter-like pattern mode suppressor as shown in Fig. 2. It is essentially based on a technique of controlling the out-of-band characteristics of the TEM mode low-pass

Manuscript received September 16, 1995; revised February 15, 1996. This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada.
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Publisher Item Identifier S 0018-9480(96)03800-8.

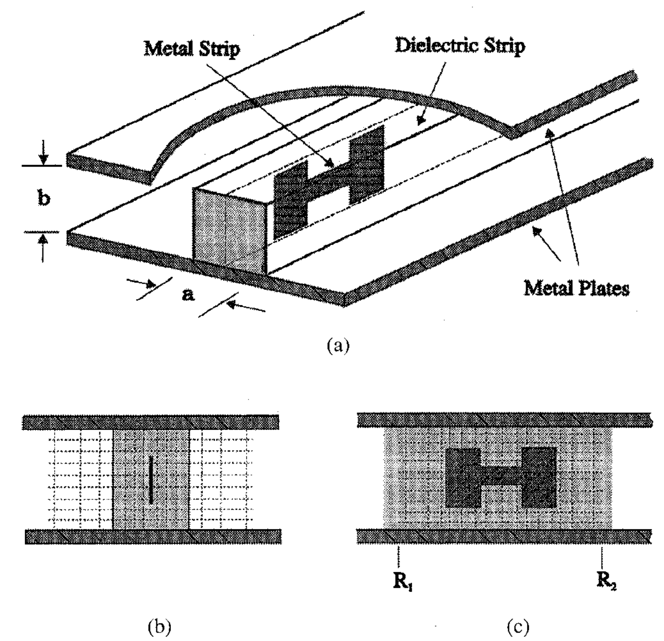

Fig. 2. (a) Structure of filter-like pattern mode suppressor. (b) Discretization layout of a TLM graded mesh for the cross-section of NRD-guide with a copper foil sandwiched in the center of the dielectric strip. (c) Discretization layout of a TLM graded mesh for the longitudinal section of NRD-guide.

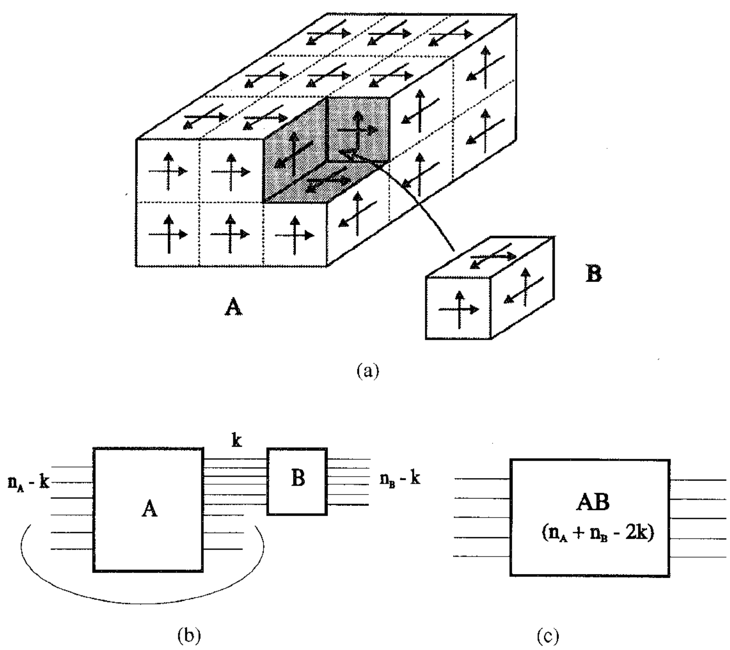

Fig. 3. Coupling and decoupling procedure in building up a FDTLM block algorithm.

filter. Therefore, the design issue of the mode suppressor is effectively transformed into a computer-aided design problem of a low-pass filter with specific attention to the out-of-band property. The resulting mode suppressor offers the advantages of being more compact and exhibiting better rejection characteristics of spurious modes than its previous counterpart [3]. In this work, a frequency-domain transmission-line matrix (FDTLM) technique [4], [5] is applied to calculate frequency-dependent S-parameters of the entire mode suppressor, including two discontinuities that are responsible for mode conversion between the LSE_{01} and TEM mode. An enhanced spectral domain analysis (SDA) [6] is used to determine propagation characteristics of the resulting suspended microtrip line that is sandwiched within dielectric for the design of a TEM mode low-pass filter. The cut-off frequency of the low-pass filter is designed and optimized such that characteristics of the upper stop-band are adjusted to provide the best rejection (suppressing) of LSE_{01} mode.

II. FDTLM Algorithm

Since the resulting structure of an NRD-guide mode suppresor is hybrid in nature, it is necessary to establish an efficient field-theoretical model for its analysis and design in an effort to account for hybrid-modes and dispersion effects. The NRD-guide in Fig. 2(a) shows a copper foil sandwiched in the middle of the dielectric strip with metal plates serving as the ground planes. The complete geometry can be viewed as a multilayered planar transmission line with cascaded discontinuities.

Frequency-dependent S-parameters of the mode suppressor can be determined by the use of a FDTLM algorithm. This field-theoretical approach is a space-discretization technique which has been well documented [4], [5]. The local electromagnetic field is defined on the surface of a condensed node. Each node can be constructed independently of its environment and characterized by a scattering matrix. By joining all the S-matrices of the nodes in the discretized space, a global S-matrix framework is obtained that describes properties of the structure under consideration.

For a given geometry as shown in Fig. 2(b) and (c), the procedure of building up a TLM algorithm for obtaining the S-parameters can be accomplished in a different way. First of all, the structure to be considered under the TLM algorithm is partitioned into a network of elements that are interconnected with each other. Note that the elements in the discrete space may be a single node or a group of nodes. The simplest approach is that each element is added into a previously combined group of elements whose S-matrix has been obtained, as shown in Fig. 3(a). In any case, two separate S-matrix blocks, namely, S_A and S_B can be considered at each step. Two S-matrix blocks are interconnected by a number, k, of common link lines (see Fig. 3(b) and (c)). This can be written in a matrix form such as

$$\begin{pmatrix} S_A^{11} & S_A^{12} \\ S_A^{21} & S_A^{22} \end{pmatrix} \cdot \begin{pmatrix} V_{A1}^i \\ V_{A2}^i \end{pmatrix} = \begin{pmatrix} V_{A1}^r \\ V_{A2}^r \end{pmatrix} \begin{matrix} \rightarrow n_A - k \\ \rightarrow \quad k \end{matrix} \tag{1}$$

$$\begin{pmatrix} S_B^{11} & S_B^{12} \\ S_B^{21} & S_B^{22} \end{pmatrix} \cdot \begin{pmatrix} V_{B1}^i \\ V_{B2}^i \end{pmatrix} = \begin{pmatrix} V_{B1}^r \\ V_{B2}^r \end{pmatrix} \begin{matrix} \rightarrow n_B - k \\ \rightarrow \quad k \end{matrix} \tag{2}$$

where the common link lines correspond to the vectors $V_{A2}^{i,r}$ and $V_{B2}^{i,r}$. n_A and n_B stand for the order of the S-matrices. Invoking the boundary conditions on the interface between the A and B blocks leads to

$$V_{A2}^i = V_{B2}^r, V_{A2}^r = V_{B2}^i. \tag{3}$$

It is easy to confirm that the S-matrix S_{AB} with an order of $n_A + n_B - 2k$, which is obtained from the combination of (1) to (3) as depicted by Fig. 3c, has the following block matrix:

$$\begin{pmatrix} S_{AB}^{11} & S_{AB}^{12} \\ S_{AB}^{12} & S_{AB}^{22} \end{pmatrix} \cdot \begin{pmatrix} V_{A1}^{i} \\ V_{B1}^{i} \end{pmatrix} = \begin{pmatrix} V_{A1}^{r} \\ V_{B1}^{r} \end{pmatrix} \begin{matrix} \rightarrow n_A - k \\ \rightarrow n_B - k \end{matrix} \quad (4)$$

in which

$$\begin{aligned} S_{AB}^{11} &= S_A^{11} + S_A^{12}(I - S_B^{22}S_A^{22})^{-1}S_B^{22}S_A^{21} \\ S_{AB}^{12} &= S_A^{12}(I - S_B^{22}S_A^{22})^{-1}S_B^{21} \\ S_{AB}^{22} &= S_B^{11} + S_B^{12}(I - S_A^{22}S_B^{22})^{-1}S_A^{22}S_B^{21} \\ S_{AB}^{21} &= S_B^{12}(I - S_A^{22}S_B^{22})^{-1}S_A^{21}. \end{aligned}$$

Any boundary condition can also be incorporated in this algorithm resulting from a block-type procedure. For example, when a metallic plate is involved, a relevant reflection coefficient for those TLM nodes located at such a metallic boundary is introduced. The corresponding complex reflection coefficient that is frequency-dependent is used to accommodate a lossy metallic boundary such as $\Gamma = (Z_c - Z_t)/(Z_c + Z_t)$ with the intrinsic wave impedance $Z_c = \sqrt{\omega\mu/2\sigma_c}(1+j), Z_t$ is the characteristic impedance of the boundary lines in the TLM mesh. Nevertheless, it should be pointed out that when the cross-section of a NRD-guide is properly terminated (see Fig. 2(b)) to simulate an open boundary, a set of mesh truncation conditions [7] have to be applied for the symmetric condensed TLM node [8]. Note that an absorbing boundary condition can be used to account for the unbounded space [10].

With the above-described recursive algorithm of block, all voltage (field) variables of the link lines between nodes are eliminated so that the global S-matrix is concerned only with incident and reflected voltages at external link lines on the designated boundary surface R_1 and R_2. Therefore, the size of the resulting S-matrix is related to the outer boundary surface of the analysis structure regardless of complexity of the geometry and volume of the structure inside the boundary surface. This property, which looks like that of a boundary element approach, is particularly useful in the analysis of a microwave integrated circuit whose boundary surface consists of waveguide cross-sections that are usually small compared to the complete volume of the circuit.

An S-parameter extraction technique has been developed in [4] in which two slices of waveguides are inserted between the semi-infinite waveguide (on both left and right sides) and the nodal-based discretized space. However, this approach becomes somewhat more sophisticated and a large number of matrix operations are involved. For a simple cross-section of the NRD-guide (see Fig. 2) which is similar to that of a rectangular waveguide, an alternative approach to extracting the S-parameters is exploited by assuming that the boundary surfaces R_1 and R_2 are located far away from the discontinuity of metallic strips [see Fig. 2(c)]. In this way, the global S-matrix of a two-port network is simplified in the form of

$$\begin{pmatrix} S^{11} & S^{12} \\ S^{21} & S^{22} \end{pmatrix} \cdot \begin{pmatrix} V_1^{i} \\ V_2^{i} \end{pmatrix} = \begin{pmatrix} V_1^{r} \\ V_2^{r} \end{pmatrix} \quad (5)$$

where are vectors of incident and reflected waves along the external link lines with respect to the left side of R_1 and the right side of R_2. To calculate the whole NRD-guide mode suppresor, an eigenvector S is first introduced which expresses the transverse field profile of a propagation mode in the discrete domain. The eigenvector S can be obtained from a 2-D eigenvalue analysis [4]. Then, one equality condition of $V_1^i = S$ and $V_2^i = 0$ in (5) gives

$$\begin{pmatrix} S^{11} & S^{12} \\ S^{21} & S^{22} \end{pmatrix} \cdot \begin{pmatrix} S \\ 0 \end{pmatrix} = \begin{pmatrix} S_{11}S \\ S_{21}S \end{pmatrix}. \quad (6a)$$

In the same manner, the other equality condition of $V_1^i = 0$ and $V_2^i = S$ leads to

$$\begin{pmatrix} S^{11} & S^{12} \\ S^{21} & S^{22} \end{pmatrix} \cdot \begin{pmatrix} 0 \\ S \end{pmatrix} = \begin{pmatrix} S_{12}S \\ S_{22}S \end{pmatrix}. \quad (6b)$$

Therefore, the S-parameters $(S_{11}, S_{12}, S_{21}, S_{22})$ can be calculated from ratios of any appropriate vector components in (6) and the defined 2-D eigenvector S [9].

Based on the above theoretical procedure, the complete transmission characteristics of a mode suppressor with the conventional choke metallic pattern [3] were obtained and compared very well with measurements as shown in Fig. 4. This indicates that the theoretical procedure presents a very accurate prediction of electrical performance for complex NRD circuits. In these calculations, the thickness of the copper foil is considered to be vanishing. This assumption seems to be reasonable for the field profile of the LSM mode which remains almost undisturbered even though the air gap will appear in the realistic situation. This is because the LSM field presents the lowest variation along the cross-section at this point. It is also fortunate that the unwanted mode is adversely affected if both the loss and thickness of the inserted metal are considered in the simulation. Using the symmetry of the structure, the number of nodes in x-direction is 6, with the graded mesh sizes of 0.25 mm, 0.25 mm, 0.25 mm, 0.3 mm, 0.6 mm, 1.0 mm, 1.5 mm, respectively. The number of nodes in y-direction is 9, with 0.25 mm, 0.25 mm, 0.25 mm, 0.25 mm, 0.25 mm, 0.25 mm, 0.2 mm, 0.2 mm, 0.1 mm, respectively. The CPU-time of the FDTLM algorithm for the 3-section mode suppressor is approximately 35 minutes for each frequency point on a HP-712. In this way, the field-theoretical technique can be used for the design and optimization of NRD mode suppresors, which will be discussed in the subsequent section.

III. Design and Optimization

Based on the well-established approximate design criteria for NRD-guides [1], [3], a Ka-band Teflon NRD-guide is chosen such that the spacing between two cover metal plates $a = 4.0$ mm and the dielectric width $b = 1.5$ mm. Under this design, the LSE_{01} nonradiative mode can only propagate in the 34–36 GHz frequency band.

To begin with, an enhanced spectral domain analysis (SDA) [6] is used to calculate propagation characteristics and characteristic impedance of such a structure including the metallic pattern as shown in Fig. 2. This is usually important in

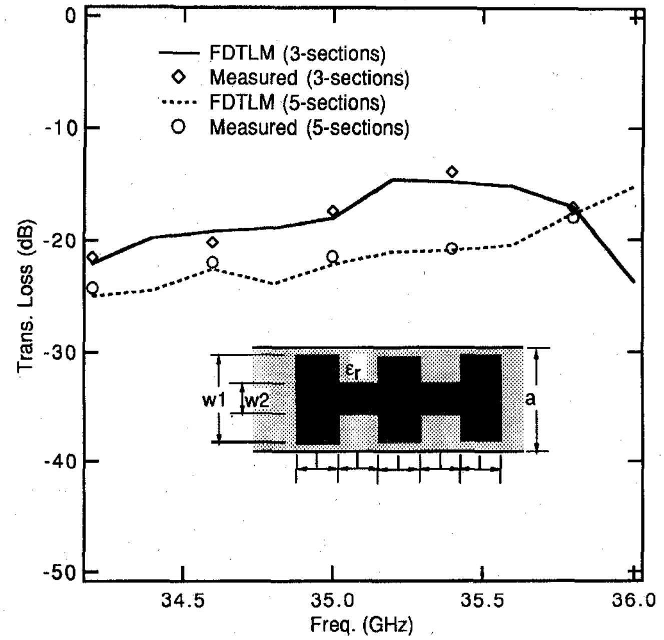

Fig. 4. Transmission loss characteristics of the LSE_{01} choke mode suppressor with $a = 4.0$ mm, $w_1 = 3.8$, $w_2 = 1.0$ mm, $b = l = 1.5$ mm, $\epsilon_r = 2.04$.

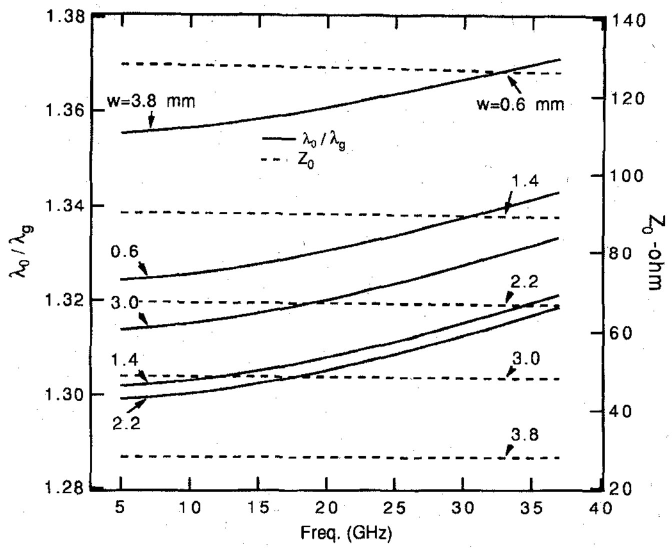

Fig. 5. Dispersion diagram of λ_g and characteristic impedance Z_0 for the structure illustrated in Fig. 2 ($a = 4.0$ mm, $b = 1.5$ mm, $\epsilon_r = 2.04$).

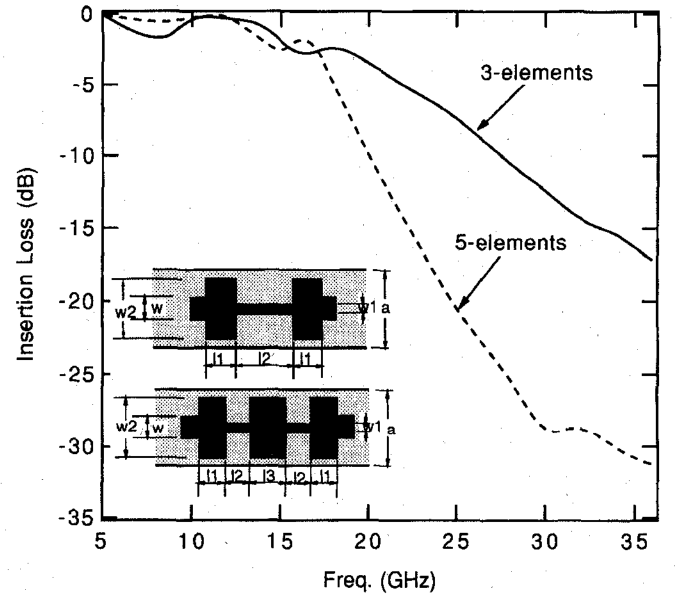

Fig. 6. Low-pass filter circuit layout and predicted frequency response of insertion loss. ($a = 4.0, b = 1.5, w = 3.0, w_1 = 1.2, w_2 = 3.6$ $\varepsilon r = 2.04$. 3-elements: $l_1 = 0.63$, $l_2 = 1.82$; 5-elements: $l_1 = 0.72$, $l_2 = 1.96$, $l_3 = 0.99$, $\epsilon_r = 2.04$. Length unit: mm.)

the design of a low-pass filter based on conventional low- and high-impedance line design technique. Fig. 5 gives the calculated curves of dispersion and impedance for different widths of the central conductor. With these results, a low-pass filter can be readily designed by applying the standard low- and high-impedance technique. To do so, a 50 Ω line with a central strip width of $w = 3.0$ mm is selected as the input and output ports of the filter in question. Fig. 6 shows the predicted electrical performance of such a low-pass filter with three- and five-elements. The cutoff frequency is designed to be 18 GHz to provide a better attenuation (rejection) at the desired suppressing band of frequency for the LSE_{01} mode. It should be noted, in this preliminary design, that the filtering characteristics are merely observed from the input TEM mode instead of the LSE_{01} mode. Therefore, considering the discontinuities responsible for mode conversion at the input and output ports, an unexpected spurious bandpass phenomenon will take place in the desired suppressing range between f_1 and f_2 even though an optimized low-pass filter is obtained as shown in Fig. 7. As a matter of fact, the discontinuities at both the input and output ports generate some additional reactances that will inevitably cause a frequency shift. It is worthwhile mentioning that only the mode suppressor is wanted and designed while the use of the filter design is really an intermediate consideration in the optimization procedure. Judging from these factors, it is absolutely necessary to use the field-theoretical model to consider the mode conversion and discontinuity effects.

With the above theoretical studies, a complete mode suppressor can be optimized from the preliminary results that are obtained by the low-pass filter modeling as well as the low- and high-impedance procedure. To effectively exploit advantages of the FDTLM algorithm in the optimization procedure, a mode suppressor can be divided into a series of sequentially cascaded sections such as step discontinuities and homogeneous NRD-guides that interconnect these discontinuities, and, at the same time, which form the input and output ports of the mode suppresor. The low- and high-impedance lines and two step discontinuities responsible for mode conversion are individually calculated first by the proposed FDTLM algorithm; the whole structure can then be simulated by an equivalent cascaded two-port network. As such, the overall filtering characteristics can be easily determined by combining S-matrices of all the sections. Although it is also possible to use the FDTLM algorithm to

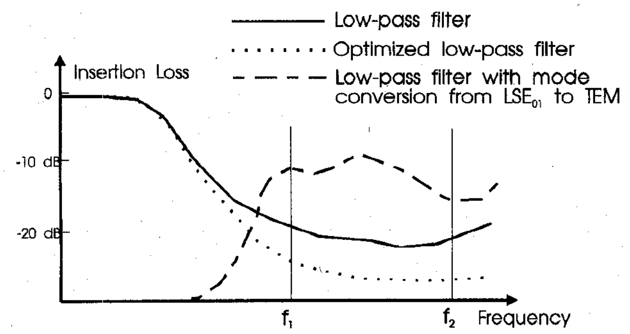

Fig. 7. Schematic illustration of frequency responses of the low-pass standard and optimized prototypes with and without the influence of mode conversion between the TEM and LSE modes for the design and optimization of NRD mode suppressor.

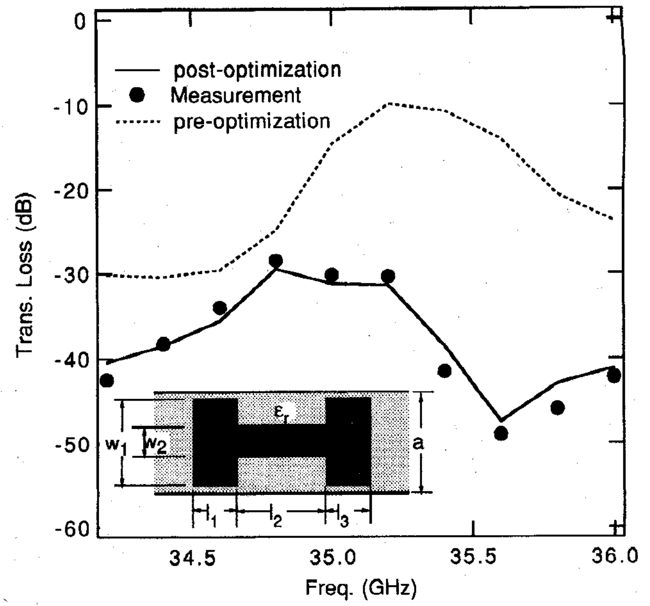

Fig. 8. Transmission loss characteristics of the filter pattern LSE_{01} mode suppresser with $a = 4.0, b = 1.5, \epsilon_r = 2.04$. Before optimization: $w_1 = 3.6, w_2 = 1.2, l_1 = l_3 = 0.83, l_2 = 1.82$; After optimization: $w_1 = 3.8, w_2 = 1.4, l_1 = 1.1, l_2 = 1.7, l_3 = 0.99$. Length unit: mm.

model and design the entire geometry of the mode suppressor, the design procedure is of course much more involved and time-consuming since a large number of parameters should be considered and adjusted simultaneously. However, the segmentation and desegmentation procedure can be effectively used in conjunction with the field-theoretical technique because the cross-coupling influence of the divided elements on the complete mode suppressor can be easily tuned by the field-theoretical modeling. Since the frequency-dependent S-parameters become available for various discontinuities and sections, an efficient and fast optimization procedure can be used by application of the multi-variable Powell method. This optimization attempts not only to improve electrical performance of the mode suppressor but also to shorten its physical length. The latter consideration is important for most NRD circuits such as power divider/combiner in which the interconnection is required to be compact and the path loss has to be minimized at millimeter-wave frequencies.

A new mode suppressor with a filter pattern is designed and optimized with a three-element low-pass prototype. In this case, the cutoff frequency is specified at 24 GHz. As shown in Fig. 8, the dotted lines present the initial design which ignores the mode conversion problem of the discontinuities at the input and output ports. It is obvious that an unexpected spurious bandpass occur around 35 GHz. Through the use of optimization, an excellent out-of-band rejection of the filter occurs. This clearly indicates that a very good compact three-element mode suppressor can be realized with the band rejection performance of more than 30 dB over the full band of frequency. This has been confirmed by measurements.

IV. Conclusion

A new class of NRD-guide mode suppressors are proposed for wideband applications of NRD integrated circuits. A filter-like design technique was used to design and optimize the mode suppressors with a designated electrical performance. This technique, based on the low-pass prototype, allows an effective out-of-band control of rejection characteristics. A novel procedure using the FDTLM algorithm was also developed to determine S-parameters of various discontinuities which were used to predict the filtering characteristics of the proposed mode suppressors. It was found that the theoretical prediction and experimental results were in excellent agreement for a large number of structures. With the proposed design technique, a three-section mode suppressor has been designed and optimized to achieve a transmission loss better than −30 dB over the full frequency band of interest. These interesting characteristics were also confirmed by measurements. The results presented in this work indicate that a compact and high-performance mode suppressor can be realized. The field-theoretical modeling is useful for analysis and design of these complex structures.

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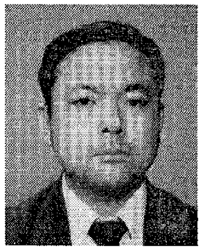

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