ANALYSIS OF THE EFFECTS OF METAL DISCONTINUITIES IN NONRADIATIVE DIELECTRIC WAVEGUIDE

Carlo Di Nallo, Fabrizio Frezza, Alessandro Galli, and Paolo Lampariello

Electronic Engineering Department - "La Sapienza" University of Rome, Italy

Abstract

The introduction of thin metallic elements (sheets, chips, etc.) is usual practice for a variety of devices in nonradiative dielectric (NRD) guide technology. The unexplored discontinuity effects due to such metal obstacles inserted in the NRD guide are theoretically investigated in this work. The transmission-line circuit characterization of the most typical metalizations (used for instance in NRD-guide mixers and oscillators) is achieved through a rigorous variational approach. The numerical implementation is then carried out for a vertical symmetrical diaphragm. Making also use of a reference approach developed through a FEM code, the reactive effects due to such discontinuities are quantified and discussed as a function of the structural parameters.

Introduction

The nonradiative dielectric (NRD) waveguide, proposed by Yoneyama and Nishida in 1981, represents an increasingly popular component for integrated circuits at millimeter waves, showing several advantages such as extremely reduced interference and radiation problems, limited losses, and compactness [1].

In parallel with the growing of the theoretical work, a lot of applications based on this structure have been developed in practice: in addition to NRD passive devices (junctions, couplers, filters, etc. [1,2]), more recent interests involve the design of active devices (oscillators, mixers, amplifiers, etc. [3,4]). In these components, a number of constitutive metallic parts such as chip elements, bias chokes, matching stubs, mode suppressors, etc., are usually introduced inside the NRD guiding structure. Typical arrangements requiring metalizations can be found in [3,4] (a beam-lead diode mount, a HEMT chip carrier for NRD amplifiers, etc.).

The characterization of the discontinuity effects on the propagation behavior of the NRD guide due to such metalizations is a problem of basic importance for the correct design of these components, but no relevant information is still achievable in the literature. Therefore, as a first schematization for a significant class of practical problems, here we face the effects of thin metal sheets in NRD guide.

Our theoretical approach is based on a rigorous variational formulation, which allows us to calculate the transmission-line circuit parameters. The effective implementation is then considered for a symmetrical vertical diaphragm. Interesting results are presented and discussed, as functions of the geometrical and electromagnetic parameters. Tests and comparisons are led by considering also a reference approach that we have developed through a commercial FEM code.

Characterization of metal sheets in NRD guide

The typical discontinuity problem under investigation is globally schematized in Fig. 1, with the relevant rectangular coordinate system and other parameters.

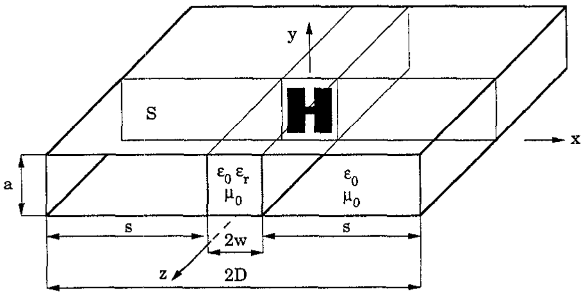

Fig. 1. *3D*-view of a laterally-closed NRD guide with a thin metallic *xy*-symmetric discontinuity at the section *z=0*, and structural parameters.

All the parts of the structure are assumed lossless. The NRD guide is constituted by a dielectric rod (permittivity $\varepsilon_0\varepsilon_r$, permeability μ_o; height a, width $2w$), which is sandwiched between parallel metal plates whose separation distance, a, is less than half the free-space wavelength λ_o (the air region outside the dielectric rod is assumed as vacuum): in this way, the fields result generally guided in the dielectric and evanescent in the air.

Two vertical metal enclosures are added laterally at a sufficiently wide distance s from the dielectric/air interface, as usually occurs in practical applications; from a theoretical viewpoint, it should be reminded that such lateral boxing does not substantially affect the surface-wave behavior and gives the advantage of avoiding the continuous spectrum of radiation modes in the open geometry [5] and any possible leakage effect [6]. Our 'closed' NRD guide is then large $2D$, where $2D=2w+2s$.

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A metal discontinuity is considered inside the dielectric rod at the $z=0$ section. The obstacle is assumed to be constituted by infinitely-thin metallic sheets, chosen horizontally and vertically symmetrical (i.e., with respect to the $x=0$ and $y=a/2$ planes), as is usual in the practical arrangements (e.g., in the metalization for the beam-lead diode). The generic transverse section of the guide is indicated with S, whereas the region excluding the area of the obstacle is indicated with S_o.

Complete set of orthonormal modes in NRD guide

As is well known, the complete modal set in NRD guide is constituted by *LSM* (i.e., $TM^{(x)}$) and *LSE* (i.e., $TE^{(x)}$) modes, whose components are derivable as functions of x-oriented vector electric and magnetic potentials [7,8]. The presence of the horizontal plates discretizes the vertical wavenumber k_y, so that $k_y=m\pi/a$, with integer m. In the closed NRD guide, also all the horizontal wavenumbers $k_{x\varepsilon}$ and k_{xo} (in the dielectric and in the air, respectively) are discretized, and they are obtained numerically as solutions of suitable characteristic equations, derivable by a typical transverse resonance approach. The horizontal eigenvalues for both *LSM* and *LSE* modes can then be ordered in terms of an integer index n. Therefore, the classification is usually given in terms of LSM_{nm} and LSE_{nm} modes (the operating mode of NRD guide is the LSM_{01}, which presents a half-sinusoid vertical dependence).

To associate a transmission-line formalism to our problem, we have to derive the characteristic impedances $Z^{M/E}$ of the NRD-guide *LSM*/*LSE* modes, propagating along the z-direction (the quantities that are referred to *LSM* and *LSE* modes will be labeled for brevity with M and E indices). The impedances can be defined according to well-stated expressions valid for *LSM*- and *LSE*-type modes [9], related to the ratio between electric and magnetic normal transverse components. We have chosen:

$$Z^M = \frac{h^2}{\omega\varepsilon_0\varepsilon_r\kappa} \quad , \quad Z^E = \frac{\omega\mu_0\kappa}{h^2}$$

where κ is the modal propagation wavenumber along z and $h^2=\kappa^2+(m\pi/a)^2$.

The proper amplitudes of the electric and magnetic transverse modal functions, $\mathbf{e}_{nm}(x,y)$ and $\mathbf{h}_{nm}(x,y)$, may be calculated through the orthonormality condition, which for *LSE* and *LSM* modes can be expressed in the form:

$$\int_S \mathbf{z}_0 \cdot \mathbf{e}_{ij}^{\alpha} \times \mathbf{h}_{kl}^{\beta}\, dS = \delta_{ik}\, \delta_{jl}\, \delta_{\alpha\beta} \quad , \quad \alpha,\beta=E,M$$

We notice that since our structure is lossless, the given orthonormality relation is valid also with the complex conjugate value for the magnetic field [7].

Variational formulation for discontinuities in NRD guide

The metal discontinuity in NRD guide gives rise to a reflected wave and a storage of reactive energy, that can be properly characterized in a global way through the transmission-line formalism. The circuit element which represents the discontinuity effect is achievable according to a classical variational approach [7,8].

With respect to most typical problems (inductive or capacitive diaphragms either in parallel-plate or in rectangular waveguides), the analysis of the effects of the NRD-guide discontinuity here considered is much more involved, since higher-order modes of both LSM_{nm} and LSE_{nm} type are excited, with both n and m indices varying since the symmetry can be broken in the horizontal and also in the vertical directions.

For the problem schematized in Fig. 1, the presence of an incident wave at port 1 ($z<0$) is considered in the form of the usual operating mode, LSM_{01}. Due to the spatial variation of the incident LSM_{01} mode (a perfect electric wall and a perfect magnetic wall can be placed at the planes $x=0$ and $y=a/2$, respectively), the horizontally and vertically symmetric discontinuity will excite modes with indices of the type $LSM_{2r,2s+1}$ and $LSE_{2r+1,2s+1}$ (with r and s null or integer).

In standard conditions, the frequency operating range is chosen so that all the higher-order modes are attenuated along the propagation direction z. In this way, if we consider for instance a $z<0$ section, the total transverse electric field $\mathbf{E}_t^{<}(x,y,z)$ is given by the sum of the contributions for the incident and reflected operating mode and for the reflected attenuated higher-order *LSM* and *LSE* modes:

$$\mathbf{E}_t^{<} = \mathbf{e}_{0,1}^{M}\, e^{-j\kappa_{01}^{M} z} + \sum_{r=0}^{\infty}\sum_{s=0}^{\infty} b_{2r,2s+1}^{M}\, \mathbf{e}_{2r,2s+1}^{M}\, e^{+j\kappa_{2r,2s+1}^{M} z} + \sum_{r=0}^{\infty}\sum_{s=0}^{\infty} b_{2r+1,2s+1}^{E}\, \mathbf{e}_{2r+1,2s+1}^{E}\, e^{+j\kappa_{2r+1,2s+1}^{E} z}$$

The amplitudes of the reflected modes (with respect to the unit amplitude of the operating LSM_{01} mode) are indicated through the $b^{M/E}$ coefficients (in particular, $b_{0,1}^{M}$ is the reflection coefficient of the operating mode). With analogous procedure it is possible to express the total transverse electric field $\mathbf{E}_t^{>}(x,y,z)$ for a $z>0$ section.

At the section $z=0$, the transverse fields must satisfy the usual continuity conditions: in particular, the transverse electric field has to be continuous on the section S ($\mathbf{E}_t^{<}(x,y,0)=\mathbf{E}_t^{>}(x,y,0)=\mathbf{e}_t(x,y)=\mathbf{e}_t(\mathbf{r}_t)$, and it is null on the metal sheets), while the transverse magnetic field has to be continuous on S_o. By applying such conditions, it is possible to express the discontinuity effect in terms of the equivalent shunt admittance at $z=0$ related to the operating-mode transmission line; the admittance is a pure susceptance jB resuming the reactive effects at the discontinuity, and after some analytical manipulations it assumes the form, normalized to the operating-mode impedance:

$$B = \frac{\displaystyle\int_{S_o}\int_{S_o} \mathbf{e}_t(\mathbf{r}_t) \cdot \overline{\mathbf{G}}(\mathbf{r}_t, \mathbf{r}_t') \cdot \mathbf{e}_t(\mathbf{r}_t')\, dS'\, dS}{Y_{0,1}^{M} \left(\displaystyle\int_{S_o} \mathbf{z}_0 \cdot \mathbf{e}_t(\mathbf{r}_t) \times \mathbf{h}_{0,1}^{M}(\mathbf{r}_t)\, dS \right)^2}$$

The expression has been compacted by introducing a dyadic kernel $\overline{\mathbf{G}}$, which takes into account the contribution of all the higher-order modes:

$$\overline{\mathbf{G}}(\mathbf{r}_t, \mathbf{r}_t') = -2j \{ \sum_{r=0}^{\infty} \sum_{s=0}^{\infty} Y^M_{2r,2s+1} [\mathbf{h}^M_{2r,2s+1}(\mathbf{r}_t) \times \mathbf{z}_o]$$
$$\cdot [\mathbf{h}^M_{2r,2s+1}(\mathbf{r}_t') \times \mathbf{z}_o] - Y^M_{0,1} [\mathbf{h}^M_{0,1}(\mathbf{r}_t) \times \mathbf{z}_o] [\mathbf{h}^M_{0,1}(\mathbf{r}_t') \times \mathbf{z}_o]\}$$
$$-2j \sum_{r=0}^{\infty} \sum_{s=0}^{\infty} Y^E_{2r+1,2s+1} [\mathbf{h}^E_{2r+1,2s+1}(\mathbf{r}_t) \times \mathbf{z}_o] [\mathbf{h}^E_{2r+1,2s+1}(\mathbf{r}_t') \times \mathbf{z}_o]$$

Such functional form of the susceptance has been proved to be stationary for small arbitrary variations in the electric field distribution about its correct value. Therefore, the previous relation represents the reference variational expression for the susceptance characterizing the diaphragm in NRD guide, from which its computation is derived.

Application to a vertical diaphragm in NRD guide

As a first application of such variational formulation for metal discontinuities in NRD guide, the interesting but particularly involved case of a symmetric vertical diaphragm has been implemented. As illustrated in Fig. 2, the obstacle is assumed to be constituted by two infinitely-thin metallic sheets (height a and width t), having one edge that coincides with the external edges of the dielectric. The part of the dielectric strip that remains open has width $2d$, where $2t+2d=2w$.

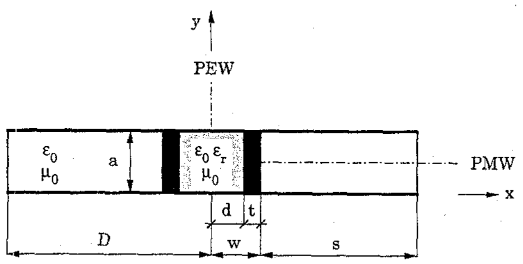

Fig. 2. Section view of a symmetric vertical diaphragm discontinuity in NRD guide, and structural parameters. Due to the symmetries of the problem, both a vertical perfect electric wall and a horizontal perfect magnetic wall may be introduced.

Such diaphragm will excite higher-order modes having the same vertical dependence $m=1$ of the operating mode, since in this case the vertical symmetry is maintained.

The procedure that leads from the variational expression of the susceptance to its effective computation has here been derived on the basis of a Rayleigh-Ritz approach.

By applying the stationarity condition ($\partial B / \partial b_n = 0$) to the previous variational expression of the susceptance, it is possible to reach a linear equation system of the type:

$$\sum_{p=0}^{\infty} \left(D_{np} - Y^M_{0,1} \, C_n \, C_p \, B \right) b_p \quad , \quad n=0,1,2,\ldots,$$

where the following integral quantities have been defined ($\mathbf{f}_n$ are the expanding functions for the unknown tangential electric field):

$$C_n = \int_{S_o} \mathbf{z}_o \cdot \mathbf{f}_n (\mathbf{r}_t) \times \mathbf{h}_{0,1} (\mathbf{r}_t) \, dS$$
$$D_{np} = \int_{S_o} \int_{S_o} \mathbf{f}_n (\mathbf{r}_t) \cdot \overline{\mathbf{G}}(\mathbf{r}_t, \mathbf{r}_t') \cdot \mathbf{f}_p (\mathbf{r}_t') \, dS' \, dS$$

The previous expressions can be represented in terms of the quantities I_{np}, which have been calculated analytically as functions of the horizontal eigenvalues:

$$C_n = I_{n0} \quad , \quad D_{np} = -2j \sum_{q=1}^{\infty} Y_{1,q} \, I_{nq} \, I_{pq}$$
$$I_{np} = \int_{S_o} \mathbf{z}_o \cdot \mathbf{f}_n (\mathbf{r}_t) \times \mathbf{h}_{p,1} (\mathbf{r}_t) \, dS$$

Then the susceptance B is calculable by imposing the annulment of the linear system's determinant.

Different sets of basis functions have been tested and compared concerning the accuracy and the stability of the results. For instance, the choice of field expansion in terms of NRD-guide LSE and LSM modal functions gives serious troubles, because the series expressing the D_{np} quantities may not converge or may converge very slowly. A substantial improvement in both the convergency speed and the accuracy of results has been obtained by choosing a field expansion in terms of trigonometric functions in both the regions (dielectric and air) aside the metal sheet.

In order to get comparative information, the problem of metal discontinuities in NRD guide has here been approached also by means of a commercial code based on the finite element method (FEM) [10].

The analysis of the results for the vertical diaphragm in NRD guide shows a general good agreement between the data obtained with the variational method and finite elements. In particular, the variational method, which is largely favourable in terms of computing speed and memory occupation, has shown in some critical cases better convergency properties than FEM. On the other hand, the FEM code presents a wider versatility of applications, even though the variational formulation can be implemented quite easily also for other discontinuity geometries.

Results and discussion

A parametric analysis has allowed us to establish the general basic features of the diaphragms in the NRD guide. As regards the vertical metal sheet, it is interesting to note at first that the discontinuity effect is strongly influenced by its position inside the dielectric strip. Other parameters being equal, it has been verified that the disturbance is more effective when the sheets are inserted towards the external border of the dielectric rod: this is due to the fact that the metallic sheet on the external border deeply alters the guidance behavior occuring at the dielectric/air interface. E.g., two limit situations occur when the same symmetric sheets are inserted either just at the center or just at the border of the dielectric strip: typically, with the central sheet the transmission coefficient is about equal to unity, whilst with the lateral sheet it is the reflection coefficient to be nearly equal to unity.

Referring now only to the most effective case of the sheet placed externally (as schematized in Fig. 2), it has also been investigated how the diaphragm contributes to the reflected and transmitted waves as frequency varies. The results shown in Fig. 3 are referred to the scattering parameters as a function of frequency for a fixed value of the ratio t/w between the metal's and the dielectric's widths: typically, S_{11} decreases and S_{21} increases with frequency.

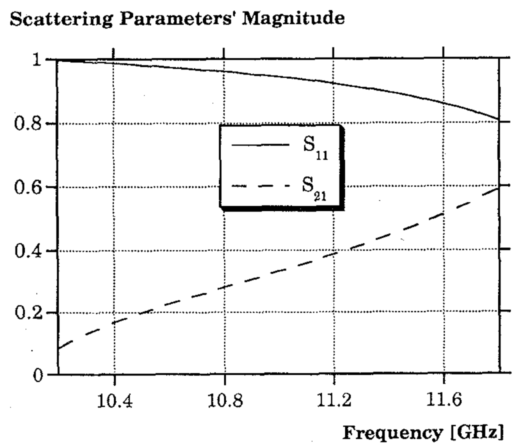

Fig. 3. Symmetrical vertical diaphragms in the lateral position: behaviors of the amplitudes of the scattering parameters S_{11} and S_{21}, as a function of frequency f (in the range between *10.2* and *11.8 GHz*), for a fixed value of the ratio t/w, evaluated through the variational formulation. *Parameters:* ε_r*=2.53; a=12.3 mm; w=5 mm; D=25 mm; t=2.5 mm.*

It can be seen that, as the metal portion increases, a stronger and stronger mismatching occurs, tending to a short-circuit situation. These behavioral features can be verified also in terms of the normalized susceptance describing the discontinuity. The diaphragms appear to give generally reactive effects that are globally of inductive type (B is negative). In Fig. 4 we show typical behaviors for B as a function of frequency for different values of the ratio t/w.

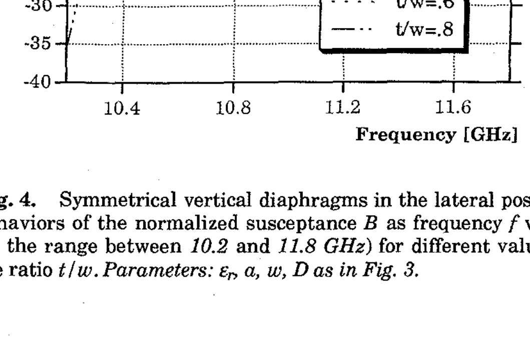

Fig. 4. Symmetrical vertical diaphragms in the lateral position: behaviors of the normalized susceptance B as frequency f varies (in the range between *10.2* and *11.8 GHz*) for different values of the ratio t/w. *Parameters:* ε_r*, a, w, D as in Fig. 3.*

Conclusion

The problem of the characterization of the effects on the propagation behavior due to metal discontinuities in NRD guide is an important aspect for the correct design of a large number of devices. This unexplored subject is considered here, and, as a first suitable schematization for a number of typical practical problems, we have investigated and quantified the effects of thin metal sheets inserted in the NRD-guide rod.

To evaluate the reactive contributions related to the below-cutoff hybrid *LSM* and *LSE* higher-order modes on the operating mode, the transmission-line circuit parameters have been derived through a general variational formulation. Even if the relevant numerical implementation presents some delicate aspects, the obtained results have shown a good precision with rather limited computing resources.

In particular, the susceptance and the scattering parameters for the operating mode have numerically been quantified for a symmetric vertical diaphragm. Controls on the data have been led considering a reference commercial code based on finite elements, whose results appear also accurate but require much more computing time and memory storage. A parametric analysis has then been carried out, thus allowing us to enlighten previously unexplored behavioral features concerning the reactive effects of metal sheets in NRD guide.

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