Analysis of Photonic Band Gap using Multilayer Contribution of Wave Concept Iterative Process MLC-WCIP

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Abstract – Microstrip elements are modeled in multilayered contribution. An iterative method based on the concept of waves is developed in a form useful for efficient computation for interacting microstrip elements, which may be located at any substrate layer and separated by a large distance. The multilayer contribution of iterative method is developed in the spatial domain. Examples for regularly shaped geometries in multilayered media are presented. These involve the optimization of a microstrip ring with a narrow gap which induces multiple reflections with a fixed phase correlation necessary to make the photonic band gap. The analysis takes into account eventual coupling parasites. Experimental measurements are performed to validate the computation. The approach involves the mixed magnetic and electric field equation technique and the wave concept iterative process which involves S-parameters extraction technique. In this sense, a program in FORTRAN has been elaborated to determine different parameters S_{ij} characterizing the studied structure. A good agreement between numerical and reported results is important to validate the theory of the multilayer contribution of iterative method MLC-WCIP.

Keywords: MLC-WCIP, multilayered structures, and photonic band gap.

I. INTRODUCTION

In the design of microwave monolithic integrated circuits (MMIC's) and millimeter-wave integrated circuits, electromagnetic (EM) modeling of microstrip elements (interconnects, antennas, and circuits, PBG) becomes important as the operating frequency becomes higher. Full-wave analysis includes the effects of EM coupling, surface waves, and radiation loss while traditional quasi-static methods and equivalent waveguide models fail to yield sufficiently accurate results. Moreover, discontinuities are inevitable in a microwave integrated circuit (MIC). Their electromagnetic property is a core issue in the design procedure. The discontinuity can be characterized by the spectral-domain approach [1], [2] or the spatial-domain technique [3, 4]. When the geometry of the circuit is complex, no matter which domain is used, the active parts, i.e., conductors in a microstrip-type problem or apertures in a slot-type problem, are divided into sub-regions for accurately determining the circuit parameters [1-5]. The incorporation of the spatial approach of the multilayer contribution of the iterative method is a general and rigorous method for analyzing planar MIC's. Furthermore, the use of multilayer circuit configuration makes microwave circuits more compact and the design more flexible [4].

In this paper, we present a simple microstrip ring which exhibit PBG characteristics, with dimensions much smaller than the conventional PBG structures. The approach involves the mixed magnetic and electric field equation technique and the multilayer contribution of wave concept iterative process which involves S_{ij} parameters extraction technique. Theoretical approach is compared with experimental measurements to validate the calculations.

II. FORMULATION

Considering multilayered structure, depicted in Fig. 1, the wave concept is introduced to express the boundary conditions on the interface air/dielectric in terms of waves [5, 6]. On each region, it is possible to characterize a scattering matrix on spatial domain and reflection coefficient on spectral domain.

The air-dielectric interface (each plane of interface) is divided into cells and includes three sub domains; dielectric (D), metal (M) and source (S). Using the boundary condition in each domain of the interface in the spatial domain (dielectric, metal, source) we can compute the scattering matrix.

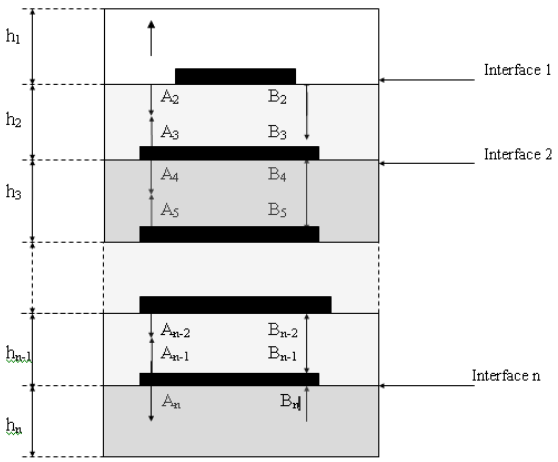

Fig. 1. Multilayered structure.

An electric field source E_0 is defined to initialize the iterative process. This source is defined on the discontinuity plane Ω in each port. So, two spatial waves with two components A_1 and A_2 are generated by the upper and lower cover of a metallic box giving two spectral waves $B_1$and B_2, which come back to the dielectric interface producing the waves for the next iteration. The incident and reflected waves can be expressed as a function of the electric field E_p and current density J_p at the plane Ω. It leads to the following set of equations [7],

$$A_p = \frac{1}{2\sqrt{Z_{op}}} \quad (E_p + Z_{op} \, J_p) \tag{1}$$

$$B_p = \frac{1}{2\sqrt{Z_{op}}} \quad (E_p - Z_{op} \, J_p) \quad , \tag{2}$$

where Z_{op} is the characteristic impedance of the medium p given by,

$$Z_{op} = \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_{rp}}} \ . \tag{3}$$

The boundary conditions in terms of waves on each cell are presented and it is function of current and electric field.

$$\begin{aligned} E_p &= \sqrt{Z_{op}}\,(A_p + B_p) \\ J_p &= \frac{1}{\sqrt{Z_{op}}}(A_p - B_p). \end{aligned} \tag{4}$$

The multilayered structures need a new formulation of the iterative method based on multilayer contribution of the WCIP taking into account the presence of middle layers p (1<p<N) which are represented by the scattering matrix and the lower surface which is characterized as a ground. The layer h_n takes an important value because it designs the lower cover of the metallic box N_p<<1.

In the spatial domain, the relation between the waves (A_p, B_p) and (A_{p+1}, B_{p+1}) in each layer is:

- In the excitation source interface p,

$$\begin{pmatrix} A_p \\ A_{p+1} \end{pmatrix} = S_{\Omega,p} \begin{pmatrix} B_p \\ B_{p+1} \end{pmatrix} + \begin{pmatrix} A_0{}^{p} \\ A_0{}^{p+1} \end{pmatrix} \tag{5}$$

$$S_{\Omega,\,p} =$$

$$\begin{pmatrix} \begin{pmatrix} -H_{p,m} \\ -\dfrac{1-n_p+n_{p+1}}{1+n_p+n_{p+1}} H_{p,s} \\ +\dfrac{1-N}{1+N} H_{p,d} \end{pmatrix} & \begin{pmatrix} \dfrac{2n}{1+n_p+n_{p+1}} H_{p,s} \\ +\dfrac{2N}{1+N^2} H_{p,d} \end{pmatrix} \\ \begin{pmatrix} \dfrac{2n}{1+n_p+n_{p+1}} H_{p,s} \\ +\dfrac{2N}{1+N^2} H_{p,d} \end{pmatrix} & \begin{pmatrix} -H_{p,d} \\ -\dfrac{1-n_p+n_{p+1}}{1+n_p+n_{p+1}} H_{p,s} \\ +\dfrac{1-N}{1+N} H_{p,d} \end{pmatrix} \end{pmatrix} \tag{6}$$

- In other interface, the relation between the waves (A_p, B_p) and (A_{p+1}, B_{p+1}) is,

$$\begin{pmatrix} A_p \\ A_{p+1} \end{pmatrix} = S_{\Omega,p} \begin{pmatrix} B_p \\ B_{p+1} \end{pmatrix} . \tag{7}$$

The matrix $S_{\Omega,p}$ becomes,

$$S_{\Omega,\,p} =$$

$$\begin{pmatrix} -H_{p,m} + \dfrac{1-N}{1+N} H_{p,d} & \dfrac{2N}{1+N^2} H_{p,d} \\ \dfrac{2N}{1+N^2} H_{p,d} & -H_{p,d} + \dfrac{1-N}{1+N} H_{p,d} \end{pmatrix} \tag{8}$$

where $N = \sqrt{Z_{0,p} / Z_{0,p+1}}$, $n = Z_0 / \sqrt{Z_{0,p} . Z_{0,p+1}}$,

$n_p = Z_0 / Z_{0,p}$, $n_{p+1} = Z_0 / Z_{0,p+1}$

Z_o is the admittance in the source zone.

$Z_{o,p}$ is the characteristic impedance of the layer p.
and,
H_m=1 on the metal and 0 elsewhere.
H_d=1 on the dielectric and 0 elsewhere.
H_s=1 on the source and 0 elsewhere.

The passage between the spatial domain and the spectral domain is obtained by 2D Fast Fourier Transform (2D-FFT) (also called Fast Modal Transform (FMT)) [8], [9]. Consequently, the waves in spatial domain $A^p \begin{pmatrix} A_x^p \\ A_y^p \end{pmatrix}$ have the expression in spectral domain,

$$\begin{pmatrix} A_p^{TE} \\ A_p^{TM} \end{pmatrix} = (2D - FFT) \begin{pmatrix} A^p{}_x \\ A^p{}_y \end{pmatrix}. \tag{9}$$

The passage between 2 adjacent layers in spectral domain of a multilayered structure needs a new formulation to describe the relationship between waves (A_p, B_p) and (A_{p+1}, B_{p+1}) in adjacent middle layers. Consequently, for $2 \leq p < n-1$, the relationship between the waves (A_p, B_p) and (A_{p+1}, B_{p+1}) is determined by using the transmission line theory (see appendix) where the scattering matrix of the transmission line [10], [11] is given by,

$$S = \frac{1}{\Delta} \begin{pmatrix} (Z_c^2 - Z_{0,p} Z_{0,p+1}) \sinh(\gamma h_{p+1}) & 2 Z_c \sqrt{Z_{0,p} Z_{0,p+1}} \\ 2 Z_c \sqrt{Z_{0,p} Z_{0,p+1}} & (Z_c^2 - Z_{0,p} Z_{0,p+1}) \sinh(\gamma h_{p+1}) \end{pmatrix}$$

$$\Delta = 2 Z_c \sqrt{Z_{0,p} Z_{0,p+1}} \cosh(\gamma h_{p+1}) + (Z_c^2 + Z_{0,p} Z_{0,p+1}) \sinh(\gamma h_{p+1}) \tag{10}$$

where Z_c: characteristic impedance of transmission line.

Equation (10) is used to define the spectral domain relationship between the waves in adjacent middle interfaces,

$$\begin{pmatrix} A_p^{TE,TM} \\ A_{p+1}^{TE,TM} \end{pmatrix} = [S] \begin{pmatrix} B_p^{TE,TM} \\ B_{p+1}^{TE,TM} \end{pmatrix}. \tag{11}$$

The passage between spectral domain and spatial domain is assured by the inverse 2D-FFT (FMT). Consequently, we have,

$$\begin{pmatrix} B^p{}_x \\ B^p{}_y \end{pmatrix} = (2D - FFT)^{-1} \begin{pmatrix} B_p^{TE} \\ B_p^{TM} \end{pmatrix} \tag{12}$$

Moreover, the reflected waves generated by the upper and lower covers of metallic box calculated by the reflection coefficient in the spectral domain,

$$\begin{pmatrix} B_i^{TE} \\ B_i^{TM} \end{pmatrix} = \begin{pmatrix} \Gamma^{TE} & 0 \\ 0 & \Gamma^{TM} \end{pmatrix} \begin{pmatrix} A_i^{TE} \\ A_i^{TM} \end{pmatrix} \tag{13}$$

where indices i (i=1, or N) defines the upper and lower patches and p(1<p<N) defines the middle patches, and,

$$\Gamma_i^{\alpha} = \frac{1 - Z_{0i} Y_{mn,i}^{\alpha} \quad \mathrm{Coth}(\gamma_{mn,i} h_i)}{1 + Z_{0i} Y_{mn,i}^{\alpha} \quad \mathrm{Coth}(\gamma_{mn,i} h_i)}. \tag{14}$$

$Y_{mn,i}^{TE} = \dfrac{\gamma_{mn,i}}{j\omega\varepsilon_0 \mu_0}$, $Y_{mn,i}^{TM} = \dfrac{j\omega\varepsilon_0 \mu_0}{\gamma_{mn,i}}$, its indices m and n mean the applied mode.

Figure 2 presents a schematic description which summarizes the main operation of the multilayer contribution of the iterative procedure.

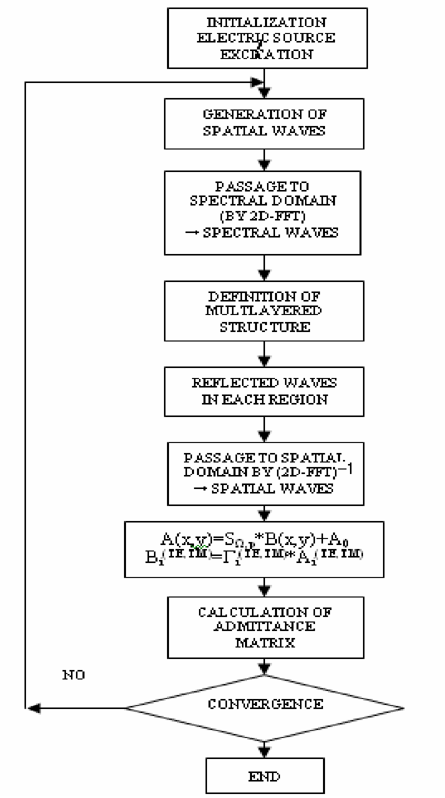

Fig. 2. Schematic description of the multilayer contribution of the iterative method.

The implementation of the iterative method establishes a recursive relationship between waves at the k and k-1 iteration, making it possible to determine the electric field and the current density at the air dielectric interface (plane p).

Finally, the two port scattering matrix S_{ij} can be obtained from the computed admittance matrix [Y] [11-12],

$$\left[S_{ij}\right]=\left[1-\left[Y\right]\right]\left[1+\left[Y\right]\right]^{-1} \tag{15}$$

III. APPLICATION

In this paper, we propose to study to analyze a Photonic Band Gap ring resonator taking into account the second interface is considered as a ground, the layer h_3 takes an important value and the dielectric constant for the third layer is $\varepsilon_r = 1$.

Figure 3 shows the geometry a regular ring connected directly to two feed line. This structure destroys the resonator character of the ring, so the semicircles of the ring can act as transmission line, and the two feed line are capacitively coupled to the ring resonator.

This microstrip structure is fabricated on a RT/Duriod 6010 substrate with the two 50Ω microstrip feed line connected directly to antipodal positions to excite the ring and to detect the output.

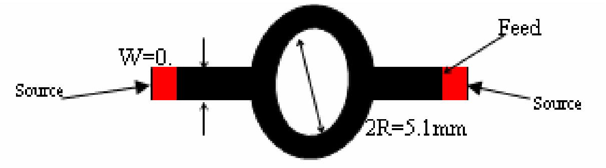

Fig. 3. Ring resonator dimension.

Figure 4 compares the simulated and measured [14] results of transmitted (S_{12}) microwaves at a ring resonator, demonstrating the accuracy of the method. We note that the regular ring shows S_{12} parameter similar to those of conventional transmission lines.

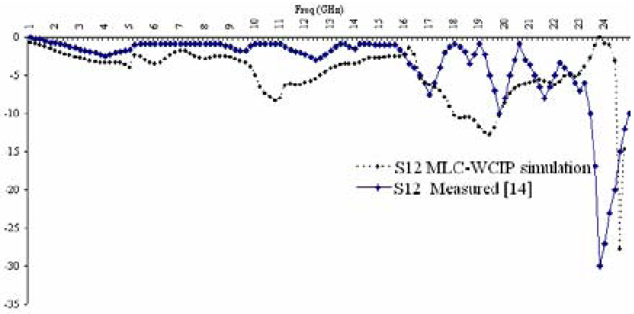

Fig. 4. Transmission coefficient $|S_{12}|$ of the ring resonator Measured vs. MLC-WCIP simulation.

Since the photonic band gap structures (PBG) can be induced from multiple reflections with a suitable phase correlation due to their strong impedance mismatch, the PBG structures can be implemented by providing structural periodicity on the microstrip line without any periodic variation in the dielectric constant of the substrate. So, a ring resonator can be modified to induce multiple reflections with a fixed phase correlation, when a small portion is removed from the closed loop assuming the feed lines are directly connected to the ring (see Fig. 5).

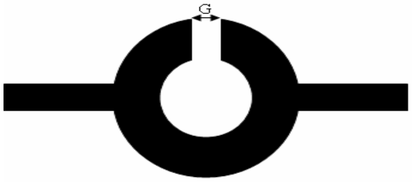

Fig. 5. Ring with gap.

Figures 6 and 7 show the excellent agreement between the measured [6] and simulated reflection coefficient S_{11} and transmission coefficients S_{12} respectively.

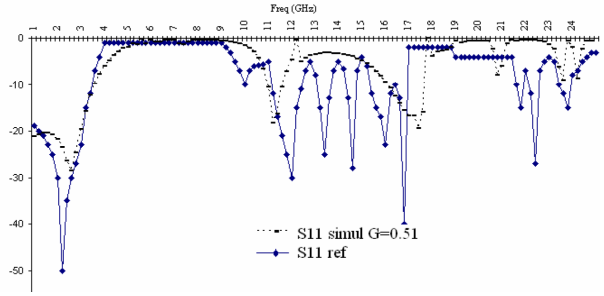

Fig. 6. Reflection coefficient S_{11} with G=0.51 of the microstrip ring with a narrow gap compared to S_{11} ref.

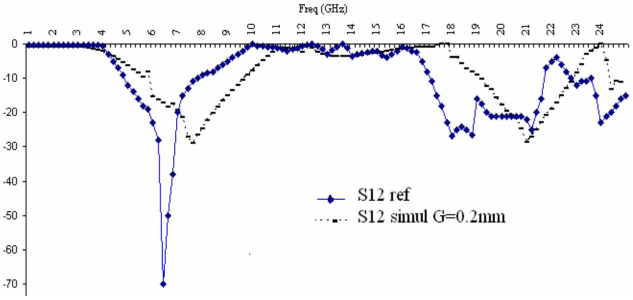

Fig. 7. Transmission coefficient S_{12} with G=0.2 of the microstrip ring with a narrow gap compared toS_{12} ref.

The impedance mismatch due the gap induces a strong attenuation valley around 6.5 GHz and 20 GHz. This corresponds to n=1 and n=3 in the following equation,

$$f_n = \frac{nc}{2\pi R\sqrt{\varepsilon_{eff}}} \tag{16}$$

where $2\pi R = n\lambda$ and $\varepsilon_{eff} = 6.77$ given by simulation by reference [14], c is the speed of light and λ is the wavelength.

We note the absence of the stop band around 13 GHz correspond to n=2 in equation (16), because the microwaves propagating along the ring are successively reflected with the fixed phase correlation when they satisfy $2\pi R - G = n\lambda$ where G=0.2mm is the dimension of the gap.

We can see clearly the characteristics of the PBG, thus the microstrip ring with a narrow gap can exhibit a PBG.

We note that the defect ground inverses the valley of the stopped band, which constitutes another advantage for the control of the stopped band in PBG structures(see Figs. 8 and 9).

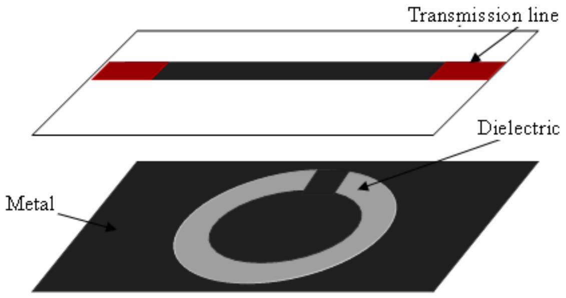

Fig. 8. The defect ground.

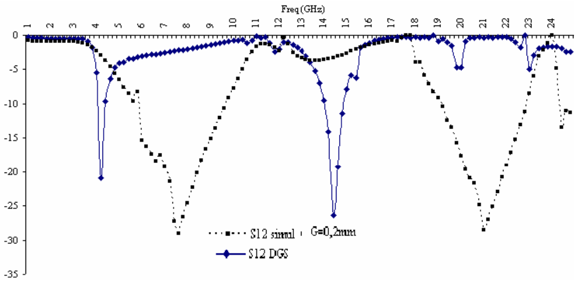

Fig. 9. Reflection coefficient for PBG and DGS structures.

IV. CONCLUSION

In this paper, we have presented an approach to the full wave analysis of multilayer substrates with the possibility of study of n- layered structures networks. This approach was used to propose a simple way to reduce the size of microwave photonic band gap structure using a microstrip ring and we discussed different techniques for the control of the stopped band. The approach involves the wave concept iterative process. Numerical results of our method are compared to measurements published in reference [14].

Other prospects of this numerical approach will be found in its combination with TLM method to constitute hybrid method able to analyze complex structures [15].

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