Analysis of A New Kind of Quadruple Folded Substrate Integrated Waveguide Filter with LTCC Technology by Wave Concept Iterative Process

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Abstract—**The article presents an efficient method named wave concept iterative process(WCIP) for characterization of substrate integrated waveguide(SIW) structures in LTCC.Firstly,an extensible approach of the iterative method to study substrates with n layers is researched.The approach involves the mixed magnetic and electric filed equation technique and the multilayer contribution of wave concept iterative process, which involves S-parameters extraction technique based on a simple form of Matched Load Simulation,and then, Substrate integrated circuits are considered as an ensemble of conducting vias placed in a parallel-plate waveguide. Finally, A new kind of multilayer SIW filter in LTCC is analyzed using the iterative method.Numerical results obtained are compared with the HFSS results. A good agreement is achieved together with significant improvements both in computational time and memory requirements.**

I. INTRODUCTION

With the development of wireless and mobile communications,more and more high-performance RF/microwave bandpass filters are required. substrate integrated waveguide(SIW) was developed to waveguide technology,Using the periodic via structure SIW can realize any passive comment listed as above in arbitrary dielectric.Although SIW filters are already much smaller and lighter as compared to those implemented with traditional waveguides, they are quite larger than conventional microstrip/stripline coupled resonator filters.However, the application of LTCC technology makes the realization of multilayered high-performance SIW filters possible[1],owing to its three-dimensional integration capabilities. Taking advantages of the multilayer nature of LTCC technology,SIW is stacked in vertical dimension[2-4].Circuit area therefore can be significantly reduced.

The analysis of substrate integrated structures and multilayer microstrip circuits has been carried out in many ways. The problem of scattering by an array of cylindrical plates was investigated using 3D methods. However, the analysis becomes more complicated when the number of the cylinders and layers increase. The problem can be simplified by considering unit cell in periodic array case, but in the case of an array with arbitrary arrangement the choice of unit periodic cell is impossible.When using the method of moments (MoM)[5], the computation of the boring Green's functions[6-8] for multilayer media are inevitable, and the slowly convergent basis functions lead to a large calculation time.For the finite elements method (FEM)[9], a great number of cells are needed to simulate the whole spatial structures and amount of memory are taken up.

In this paper, we present a novel quadruple folded SIW filter. The proposed configuration is analyzed by a new method based on the Multilayer Contribution of Wave Concept Iterative Process (MLC-WCIP)[10].The MLC-WCIP method are developed and adapted in but to resolve this type of structure. In addition, Substrate integrated circuits are considered as an ensemble of conducting vias placed in a parallel-plate waveguide. The approach is based on the wave concept formulation and the iterative resolution of two relationships between incident and reflected volume-waves[11].The reflection operator is expressed using Hankel functions and computed by considering the scattering from the ensemble of conducting posts.The simulation results are validated with those calculated with HFSS commercial code.

II. FORMULATION

A. The Operator of Reflection Based on Multilayer Substrates

The WCIP first represents the boundary condition on the upper and lower interface of circuit in term of waves[12], and then sets up relationship of the incident waves and scattered waves both in spatial and spectral domain (Figure 1). We define the incident and reflected wave in both sides of the discontinuity plane $\forall\, \mathrm{i}=1{,}2$

$$\mathbf{A}_i=\frac{1}{2\sqrt{Z_{0i}}}\left(\mathbf{E}+Z_{0i}\mathbf{J}\right)\quad \mathbf{B}_i=\frac{1}{2\sqrt{Z_{0i}}}\left(\mathbf{E}-Z_{0i}\mathbf{J}\right)$$

,

where:

$$Z_{0i}=\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_{ri}}}\,,\ \forall\, i=1{,}2$$

is the medium impedance. A and B are, respectively, the incident and the reflected waves.

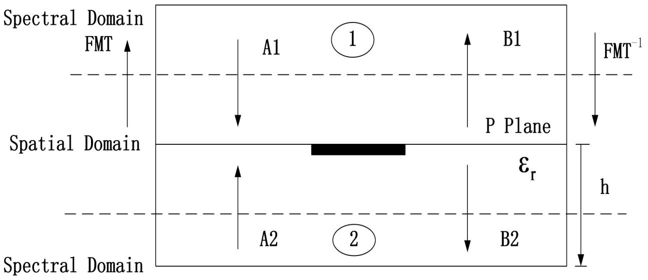


Figure 1. Definition of wave concept.

On the interface,there are dielectric, metal, and source domains. it is necessary to determine the scattering matrix on each region,so we can calculate the scattering matrix in spatial domain.It takes the following expression[10]:

$$S_M=\begin{pmatrix} -H_m-\frac{-1+n_1+n_2}{1+n_1+n_2}H_s+\frac{1-N^2}{1+N^2}H_d & \frac{2}{1+N^2}H_d+\frac{2n}{1+n_1+n_2}H_s \\ \frac{2N}{1+N^2}H_d+\frac{2n}{1+n_1+n_2}H_s & -H_m-\frac{-1-n_1+n_2}{1+n_1+n_2}H_s+\frac{1-N^2}{1+N^2}H_d \end{pmatrix} \quad (3)$$

Where

$$N=\sqrt{\frac{Z_{01}}{Z_{02}}},n_1=\frac{Z_0}{Z_{01}},n_2=\frac{Z_0}{Z_{02}},m=\frac{Z_0}{\sqrt{Z_{01}Z_{02}}}.$$

And H_j=1 on the domain j, H_j=0 elsewhere,where j=source, dielectric, or metal domain.

In spatial domain,the relationship of the incident waves and scattered waves is:

$$\begin{bmatrix}B_1\\B_2\end{bmatrix}=[S]\begin{bmatrix}A_1\\A_2\end{bmatrix}+\begin{bmatrix}\frac{E_0}{\sqrt{Z_{01}}}H_s\\\frac{E_0}{\sqrt{Z_{01}}}H_s\end{bmatrix}\qquad(4)$$

In spectral domain,the relationship between waves is as follows:

$$\begin{bmatrix}B_i^{TE}\\B_i^{TM}\end{bmatrix}=\begin{bmatrix}\Gamma_i^{TE}&0\\0&\Gamma_i^{TM}\end{bmatrix}\begin{bmatrix}A_i^{TE}\\A_i^{TM}\end{bmatrix}\qquad(5)$$

Where

$$\Gamma_i^{\alpha}=\frac{1-Z_{0i}Y_{mn,i}^{\alpha}\cot angh(\gamma_{mn,i}h_i)}{1+Z_{0i}Y_{mn,i}^{\alpha}\cot angh(\gamma_{mn,i}h_i)}$$

$$(\alpha=TE\quad or\quad TM)\qquad(6)$$

$$Y_{mn,j}^{TE}=\frac{\gamma_{mn,i}}{j\omega\varepsilon_0\mu_0},Y_{mn,j}^{TM}=\frac{j\omega\varepsilon_0\mu_0}{\gamma_{mn,i}}$$

$$\gamma_{mn,i}^2=(\frac{m\pi}{a})^2+(\frac{n\pi}{b})^2-k_0^2\varepsilon_{ri}$$

k_0 is the space number.For each iteration, we combine the wave concept with the 2D-FFT algorithm to change the type of domain. This technique is called Fast Mode Transformation (FMT).This procedure contains Fourier transform and Mode transform.The iterative procedure mechanism is summarized in Figure 2.

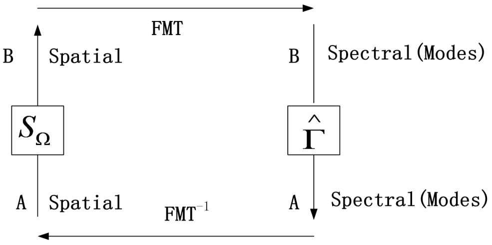


Figure 2. Schematic description of the iterative process.

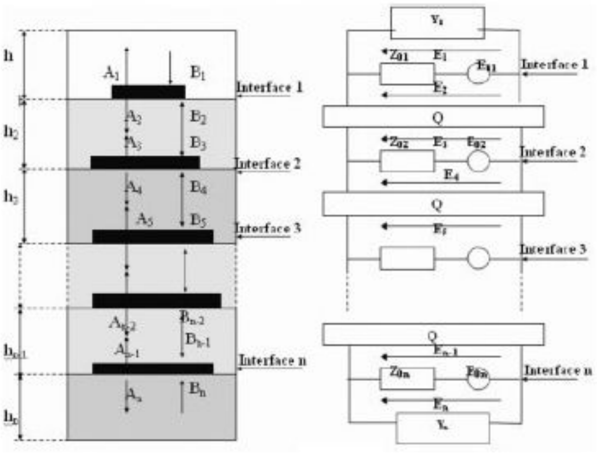
For the multilayer structure (Figure 3), the relation of waves between the layers in the spectral domain should be taken into account. Accordingly, the transmission line theory is used to express this relation[13].the scattering matrix of the transmission line is given by

$$S=\frac{1}{\Delta}\begin{pmatrix}(Z_c^{\ 2}-Z_{0,j}Z_{0,j+1})sh(\gamma h_{j+1})&2Z_c\sqrt{Z_{0,j}Z_{0,j+1}}\\2Z_c\sqrt{Z_{0,j}Z_{0,j+1}}&(Z_c^{\ 2}-Z_{0,j}Z_{0,j+1})sh(\gamma h_{j+1})\end{pmatrix}(7)$$

With

$$\Delta=2Z_c\sqrt{Z_{0,j}Z_{0,j+1}}ch(\gamma h_{j+1})+(Z_c^{\ 2}+Z_{0,j}Z_{0,j+1})sh(\gamma h_{j+1})$$

Where Z_c is the transmission line impedance, $Z_{0,i}$ is the characteristic impedance of the layer j , γ is the propagation constant in the line.



(a) (b)

Figure 3 (a) Multilayered structure and (b) its equivalent circuit

B. The Operator of Reflection Based on Substrate Integrated Waveguide

We consider the case of cylindrical wires placed between two parallel metallic plates in substrate integrated waveguide such as illustrated in Fig.4.

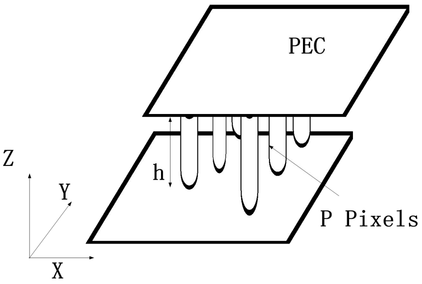


Figure 4 Cylindrical wires between two parallel metallic plates

The current density J has only z component(Jz), but it is dependent of z. he electric field can be given by the following[11]:

$$\mathrm{E}=-\nabla\phi-\frac{\partial}{\partial t}\mathrm{F}=\frac{1}{\mathrm{j}\omega\mu\varepsilon}\nabla(\nabla.\mathrm{F})-\mathrm{j}\omega\mathrm{F}\qquad(8)$$

In the Eq.(8), the potential vector F has only z component.With the presence of the parallel plates, we can consider that all electromagnetic fields are with e^{jaz} dependence with $\alpha=\frac{2q\pi}{h}$, By mathematical manipulation applied to the equation of Maxwell-Faraday Eq.(8), we obtain the following:

$$(\Delta_T+k^2)F=-u_0J\qquad(9)$$

where Δ_T is the transverse Laplace operator.Using the equation of Maxwell-Faraday with $\nabla(\nabla.F)=-\alpha^2F$, we obtain the following:

$$E=-j\omega(1-\frac{\alpha^2}{k^2})F\qquad(10)$$

To have relationship between the electric field and the current density, we combine the Eqs.(9) and (10):

$$(\Delta_T + k^2)E = -j\omega(1-\frac{\alpha^2}{k^2})uJ \qquad (11)$$

The expression (10) can be expressed as follows:

$$J = \hat{Y}E \qquad (12)$$

Where $\hat{Y} = \frac{1}{j\omega(1-\frac{\alpha^2}{k^2})}(\Delta_T + k^2)$ is the admittance operator.The relationship between incident and reflected waves is given by the following:

$$A = \hat{\Gamma}B \qquad (13)$$

where $\hat{\Gamma}$ is the reflection operator which is defined as follows:

$$\hat{\Gamma} = \frac{Y_0 - \hat{Y}}{Y_0 + \hat{Y}} \qquad (14)$$

where $Y_0 = 1/Z_0 = \omega\varepsilon$

Using the Eqs.(10), (11), (12), and (14), we can obtain the expression of the reflection operator:

$$\hat{\Gamma} = -1 + 2Y_0 j\omega(1-\frac{\alpha^2}{k^2})[\Delta_T + k^2]^{-1} \qquad (15)$$

where $k_1^2 = k^2 + jY_0\omega\mu\,(1-\frac{\alpha^2}{k^2})$

The solution of the operator $[\Delta_T + k^2]^{-1}$ is given by the expression $\frac{j}{4}\int H_0^2(k|r-r'|)d^2r'$,where H_0^2 stands for the second kind Hankel function of order zero. Thus, Eq.(13) can be rewritten as follows:

$$\hat{\Gamma}B = -B + \frac{Y_0\omega u}{2}(1-\frac{\alpha^2}{k^2})\int H_0^2(k_1|r-r'|)Bd^2r' \qquad (16)$$

III. DESIGN OF LTCC FILTER BASED ON SUBSTRATE INTEGRATED WAVEGUIDE

To demonstrate the effectiveness of the method,we consider a design of LTCC filter based on quadruple folded substrate integrated waveguide.The structure of the filter is is able to reduce the circuit size by about 85% compared with the conventional substrate integrated waveguide(SIW) resonant cavity.Fig.5 shows the proposed quadruple folded substrate integrated waveguide resonator.

As well known, substrate integrated waveguide filters usually have better performance than other planar structures.However, their use may be restricted because of the relative large physical dimension. To overcome such a drawback, some miniaturized resonant cavity structures were proposed and investigated. For example, a double-folded SIW resonant cavity was introduced in 2004 [14]. It is a two-layer waveguide resonant cavity with L-type slot in the middle conductor layer, thus it can reduce the circuit area by 75% compared with the conventional SIW resonant cavity. Some researchers made efforts to reduce the size of SIW resonant cavity as well [15-16].Nevertheless, there is still room for improvement. Filters designed with SIW waveguides and LTCC can enhances the possibility of hybridizing laminated waveguides and planar circuits with significant reduction in circuit size[17-20].

In this paper, The filter is implemented with quadruple folded SIW (QFSIW) cavity Resonators in LTCC.Conductor-backed sandwiched CPW is employed as the feeding structure to transmit power from microstrip line into the QFSIW resonant cavity. After that, a two-cavity filter is developed and fabricated based on the proposed miniaturized SIW resonant cavity.The filter is implemented on a 8-layer Ferro A6M LTCC substrate with relative permittivity of 5.9 and loss tangent of 0.002,and a uniform dielectric layer thickness of 0.096 mm.All metallic vias have the same diameter of 0.45mm. Every SIW cavity is built based on a 8-layer substrate.Fig.6 shows the proposed filter structure. the other size parameters about the two-pole filter as follows: L1=9.15mm, L2=5.65mm.L3=2.25mm, W=1.06mm,h=0.768mm,s=0.25mm,Its overall size is 9.15*9.15* 0.768mm^3.

The presented formulation was implemented in FORTRAN code. The scattering parameters S_{11} and S_{12} are shown in Figure 7. The center frequency is 9.05 GHz ,the filter has the fractional bandwidth of 11%. A good agreement between our result and the HFSS result.The computations of the structure were performed on Core(TM) I5 CPU 2.67GHz, 2 GB RAM. In Table 1, CPU time for the case considered in this article are reported. Note that the construction of the matrix Γ is independent of the iteration, thus, it can be done once in the preprocessing step.

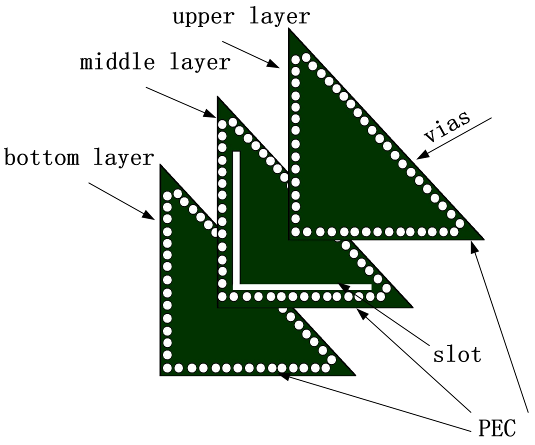


Figure 5 The proposed quadruple folded substrate integrated waveguide resonator

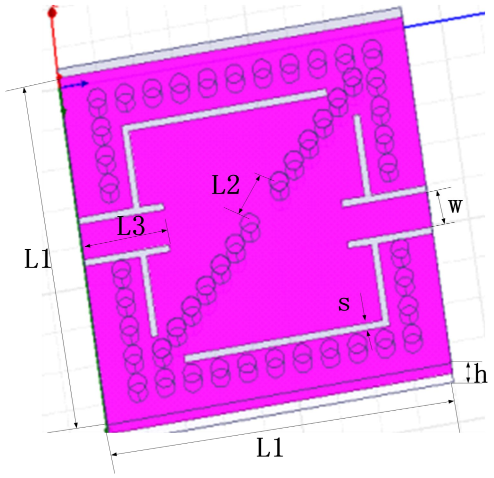


Figure 6 The proposed filter structure

IV. CONCLUSIONS

In this paper, we expand the use of WCIP, which is widely used for planar circuit, to analysis the SIW multilayer circuit—a two cavities LTCC quadruple folded SIW filter.The efficiency of the method has been shown through the analysis of test case of multilayer SIW structures, with short computational time. A good agreement is achieved between our result and the HFSS result. This new approach is found to be efficient in producing accurate results with good saving in the computer memory usage and computational time and has the capacity to simulate very large structure with large number of via holes.

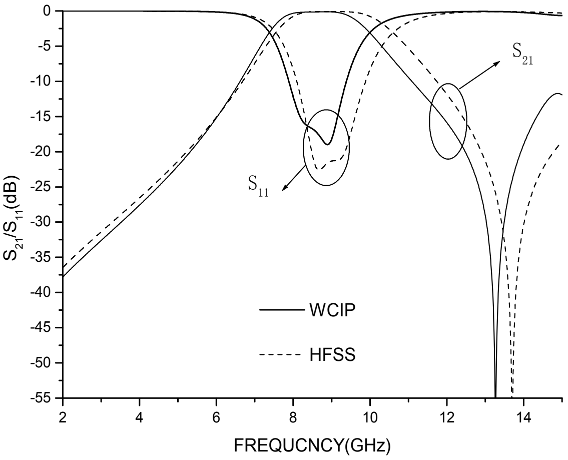


Figure 7 The proposed filter results

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TABLE1 CPU Time for the Two Cases Considered in this Article

Example	HFSS CPU Time	This Article
Filter Figure 6, 48×2vias	105s for mesh and 31s for frequency point	8s for calculation of Γ and 4s for frequency point