A Simplified Normalization FDTD Formula and Its Application to VIP Combline Bandpass Filters

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Abstract—**In this short report, new studies on the normalized finite-difference time-domain (FDTD) formula show that its time-domain iteration is done with an expanded dimension. A simple formula is derived to show the resulted variations in frequency domain. The practical application on the vertical installed planar (VIP) BPF is given, a novel improvement to which includes applying the planar fins and fine through-holes to reduce the requirement on an ideal ground circuit. The excellent properties of the modified combline BPF have been shown by the FDTD design as well as the measured ones.**

I. Introduction

SINCE Yee reported a practical finite-difference architecture in both of space and time domains for the Maxwell curl equations, the formula of three-dimensional finite-difference time-domain (3-D FDTD) has found wide applications in analyzing various microstrip circuits [1]–[3]. In this letter, we will carry out a further study on normalized FDTD formula [1] with an arbitrary factor to make its dimension expanded, then verify the program via a numerical example of a patch antenna [3], and finally, we will show the application to the VIP BPF [4] in which a new design [5] given in Fig. 1 is studied to adjust the performance of this modified microstrip combline BPF.

II. A Normalized 3-D FDTD Formula

An investigation on Yoshida's normalization FDTD equation [1] includes to introduce an arbitrary factor or difference mesh Δs into the discrete Maxwell curl equations in an isotropic media. In this short report, only the electric component e_y in the simplified 3-D FDTD formula is given

$$e_y^{n+1,0} = e_y^{n,0} + \frac{\Delta t a_y}{\varepsilon \Delta s b_x b_z} \cdot \left[\left(h_x^{n+1/2,2} - h_x^{n+1/2,1}\right) - \left(h_z^{n+1/2,2} - h_z^{n+1/2,1}\right)\right] - e_y^{n,\text{inc}}(\Delta t) \quad (1)$$

where $e_y^{n,\text{inc}}(\Delta t)$ denotes the incident wave, which is a function of Δt [1]. The first superscripts $n, \ldots, n+1/2$ represent time step recordings; the second ones $0, 1, 2$ are for the space difference points. The electrical or magnetic field components in (1) are similar to those used in double space difference step subroutines [1] such as: $e_{x,y,z} = a_{x,y,z} E_{x,y,z}$ or $h_{x,y,z} = b_{x,y,z} H_{x,y,z}$ with $a_x = \Delta x_i / \Delta s, \ldots, b_x = \delta x_i / \Delta s, \ldots,$ etc.

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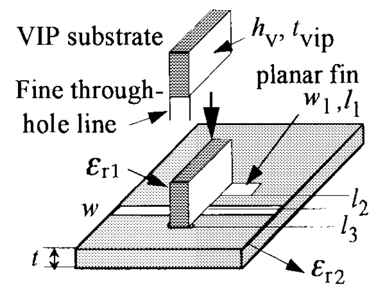

Fig. 1. VIP combline BPF.

The unit in (1) can be the same as other 3-D FDTD formulas. However, the numerical study has revealed that the time step or dimension in (1) is influenced by Δs or a nonunit factor η

$$\eta = \Delta s/\text{unit} \cong (\Delta x_i, \Delta y_j, \Delta z_k)|_{\max}/\text{unit} \quad (2)$$

where η is constant and so is the time step in (1). A further study on numerical stability condition [2] can give a useful conclusion such as $\Delta t' = \Delta t/\eta$ and it can be simply derived as

$$\Delta t'|_{\min} \le \frac{1}{\nu_{\max}} \Bigg/ \sqrt{\frac{1}{\Delta x'^2_{\min}} + \frac{1}{\Delta y'^2_{\min}} + \frac{1}{\Delta z'^2_{\min}}} \quad (3)$$

where $\nu_{\max}$ is the maximum phase velocity of the electromagnetic wave propagation [2], and difference cells are modified as $\Delta x'_{\min} \equiv \Delta x_{\min}/\eta, \ldots$. A complete demonstration on (1)–(3) can show the equations must be redefined into a new normalized system, which will be given in the future. The computation of (1) can be done via a new efficient Yee's iteration form [1], [6] with Mur's absorbing boundary condition (ABC).

As the expanded time step $\Delta t'$ always satisfies the condition $\Delta t' > \Delta t$ if $\eta < 1$ condition is considered, we can set up the frequency transform corresponding to the above-discussed process

$$f_k = \frac{k}{N_t \Delta t'} = \frac{k\eta}{N_t \Delta t}, \qquad k = 0, 1, \ldots, N_t \quad (4)$$

where f_k is the compressed frequency scaling, N_t is the maximal iteration number, and k is the index of discrete Fourier transform (DFT). In the practical application of (4), error less than about 5% must be included in the value of factor η because of the numerical iteration errors [6]. The S parameters of full-wave analysis results on different microstrip devices have demonstrated very well the correctness of (1)–(4).

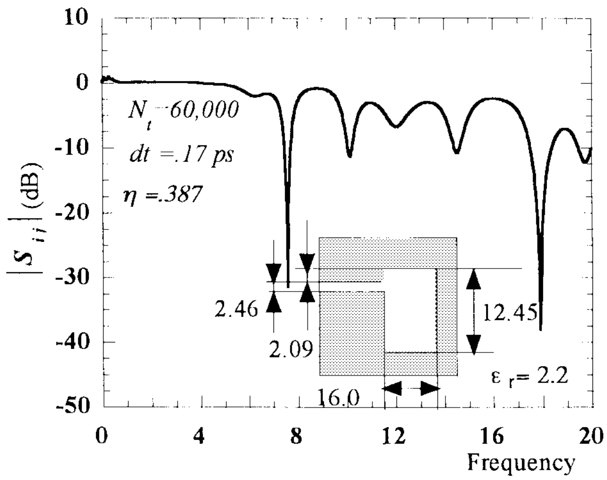

Fig. 2. Normalized 3-D FDTD simulation result on a patch antenna [3].

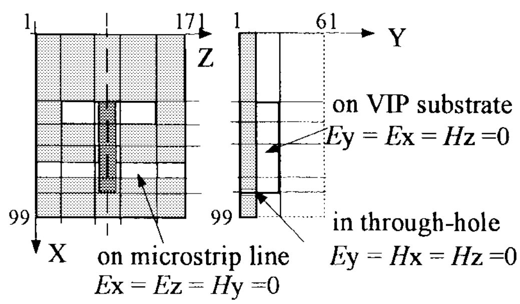

Fig. 3. VIP-C-BPF for 3-D FDTD analysis.

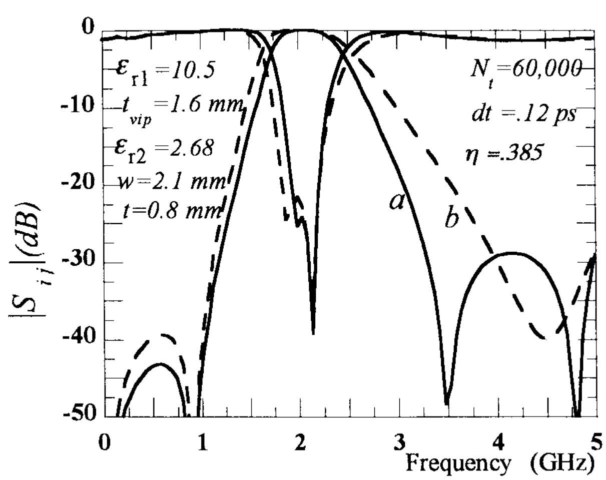

Fig. 4. Simulation results on VIP C-BPF via the normalized 3-D FDTD (unit = mm). *a*: $hv = 1548, w_1 = 6.6, l_1 = 3.5, l_2 = 4.85, l_3 = 1.45$. *b*: $hv = 1.96, w_1 = 5.2, l_1 = 5.26, l_2 = 3.39, l_3 = 1.25$.

Fig. 2 shows one of the numerical examples via the simplified FDTD on a patch antenna [3]. The time step Δt is calculated as 0.17 ps, about half of that used in [3] because the minimum mesh is also defined in the same way when the double difference iteration [1], [6] is applied. The VIP devices [5], [6] are calculated via the same program. The CPU time for simulating a device is about 300 s at the University's parallel system. The expanded time-domain FDTD can save plenty of CPU time for a 3-D structure as shown in Fig. 3.

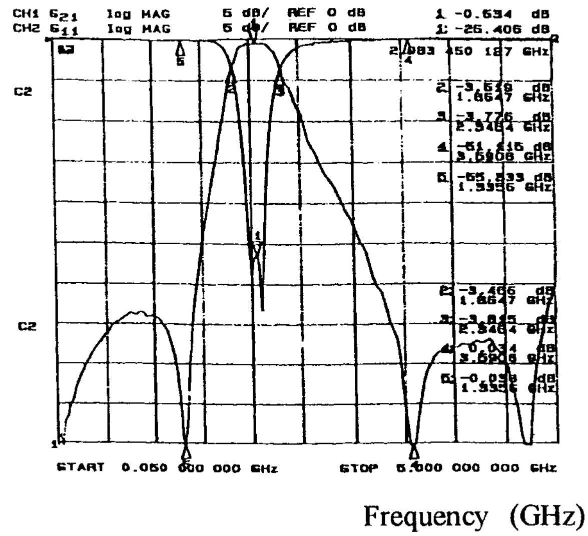

Fig. 5. Measured result for the design in Fig. 4*a*.

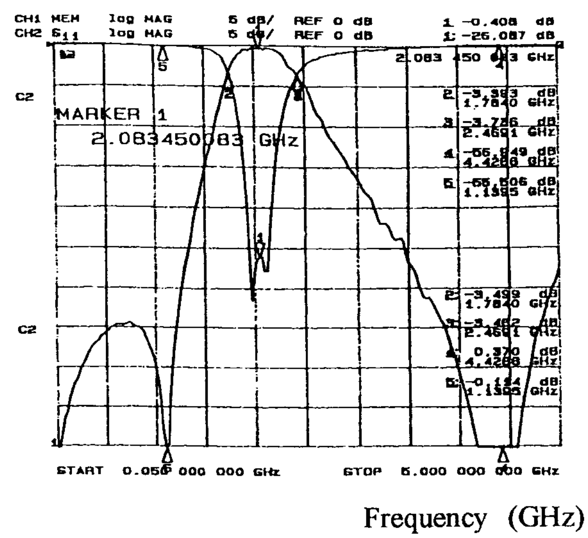

Fig. 6. Measured result for the design in Fig. 4*b*.

III. Calculations and Measurements

The S parameters on VIP combline BPF [4], [5] are calculated via this normalized FDTD. An equivalent circuit analysis [5] can show a thin wire for through-hole can generate a small inductance to a modified combline BPF and no longer requires an ideal ground design [4]. The numerical design of the filter is introduced in Fig. 3. The through-hole is simulated via a difference cell of 0.1 mm with the boundary condition of $E_y = H_x = H_z = 0$. The size is near the same as that of the wire's diameter used in the experiment. The vertical conducting planes can be simulated [6] via the condition of $E_y = E_x = H_z = 0$ and I/O microstrip line of $E_x = E_z = H_y = 0$. Those electromagnetic conditions are shown to be very effective in analyzing VIP filters.

Fig. 4 shows two designs of different fins' size and full-wave response. The dielectric constant of the vertical substrate is taken as 10.5 with a thickness of 1.6 mm. The corresponding measured results are shown in Figs. 5 and 6, where the tapping size l_3 is modified as $l_3 \approx l_{3,\mathrm{FDTD}} + W/2$ when a diameter of through-hole of about 0.5 mm was used. The structure of this microstrip BPF can be fabricated easily in the experiment.

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