Applications of Planar Multiple-Slot Antennas for Impedance Control, and Analysis Using FDTD with Berenger's PML Method

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Abstract — Folded- and multiple-slot antennas have been used for quasi-optical arrays. However, there is lack of information of these antennas, especially on finite substrates. In this paper, CPW-fed folded- and multiple-slot antennas are analyzed using FDTD technique with improved absorbing boundary condition (PML method). The effects on the effective dielectric constant and input impedance due to substrate thickness have been investigated. Furthermore, a method of controlling the resonant impedance will be presented in the conference.

I. Introduction

CPW-fed folded and multiple slots have been used in quasi-optical amplifier arrays [1],[2]. These antennas are chosen because of their simple fabrication, easy integration with three-terminal devices, and broader bandwidth compared to other planar antennas, such as patch antennas. However, little design information [3]-[5] is available for these antennas on dielectric substrates, such as resonant frequencies and input impedances, which are essential to circuit designs. This paper presents a numerical investigation of the folded- and multiple-slot antennas using the finite difference time-domain (FDTD) technique with PML absorbing boundary condition [6],[7]. The influence of antenna layout and substrate parameters on the input impedances and resonant frequencies of the antennas will be described in this paper. In addition, a method of controlling impedances of these antennas will be discussed. Using this technique, we are able to obtain a large range of impedance values at resonance. In particular, a five-slot antenna with $50\,\Omega$ input impedance has been built and tested. This antenna will play an important role in developing quasi-optical system since it can be integrated directly with commercial MMIC chips without any matching networks.

II. FDTD with PML Absorbing Boundary Condition

FDTD method has been widely used for various electromagnetic problems [8],[9]. As been pointed out in [9], reflection from the imperfect absorbing boundary condition (ABC) at the outer boundaries will create significant errors in frequency domain. Recently, Berenger proposed the perfectly matched layer (PML) ABC [6] for 2-D FDTD, which he showed can reduce the reflection by orders of magnitude. This new method has been verified by Taflove [7] and extended for 3-D FDTD. If σ and σ^* represent the electric conductivity and magnetic loss for the outer boundary layer, it is known that

$$\sigma/\varepsilon_d = \sigma^*/\mu_o \tag{1}$$

will yield zero reflection at the interface between two media. Consider transverse magnetic (TM) case in 2-D with field components H_x, H_y, and E_z. In PML region, E_z is split into two sub-components, E_{zx} and E_{zy}. Therefore, there are four, instead of normal three, field equations:

$$\mu_o \frac{\partial H_x}{\partial t} + \sigma_y^* H_x = -\frac{\partial}{\partial y}(E_{zx} + E_{zy}) \tag{2a}$$

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$$\mu_o \frac{\partial H_y}{\partial t} + \sigma_x^* H_y = \frac{\partial}{\partial x}(E_{zx} + E_{zy}) \tag{2b}$$

$$\varepsilon_d \frac{\partial E_{zx}}{\partial t} + \sigma_x E_{zx} = \frac{\partial H_y}{\partial x} \tag{2c}$$

$$\varepsilon_d \frac{\partial E_{zy}}{\partial t} + \sigma_y E_{zy} = -\frac{\partial H_x}{\partial y} \tag{2d}$$

The loss in PML region increases quadratically [6]. That is,

$$\sigma(\rho) = \sigma_{max} \left(\frac{\rho}{\delta}\right)^2 \tag{3}$$

where δ is the PML thickness. For 3-D case, all six fields are split and there are total 12 equations in PML region [7].

III. Numerical and Experimental Results

The folded-slot antenna was fabricated on Duroid 5880 substrate with thickness of 0.813 mm and ε_r=2.2. The length and the width of the slots are L=78 mm and W=G=2 mm, respectively; the separation of the two slots is S=2 mm. In FDTD simulation, Δx, Δy, and Δz are 0.3 mm, 0.5 mm, and 0.271 mm, respectively. Δt is 0.4 ps. The PML is 16 cells thick and the maximum values of (σ, σ^*) are (700 S/m, $9.95\times10^7\,\Omega$/m) in free space and (1540 S/m, $9.95\times10^7\,\Omega$/m) in the substrate. Figure 1 shows the input impedance of this antenna from both measurement and simulation. The agreement is excellent.

An important parameter for circuit designs is the resonant impedance. Figure 2 shows the dependence of the resonant impedance on substrate thickness, h, for both ε_r=2.2 and ε_r=10.8 cases. Note that L stays the same for both cases and the only parameter varies in the simulation is h. It was found that the impedance is an increasing function of thickness in the thin substrate range. For infinite substrates, the simulation yielded the input impedances of 116 Ω and 64 Ω for ε_r=2.2 and ε_r=10.8 cases, respectively, which agree with the results in [4].

It is known that the input impedance of N-element slot antenna, $Z_{in,N}$, is given by

$$Z_{in,N} = \frac{Z_{slot}}{N^2} \tag{4}$$

where Z_{slot} is the input impedance of a single slot antenna. This idea has been confirmed both theoretically and experimentally. The antennas were fabricated on 0.635 mm Alumina substrates with ε_r=9.8. Figure 3 shows the drawings and dimensions of two-, three-, four-, and five-slot antennas. The measured and theoretical input impedances of these antennas are shown in figure 4. It is clear that the impedance is scaled down with the additional slots according to (4) and their values cover quite a large range. The important observation from this figure is that with five slots, the input impedance is $\approx 50\,\Omega$. Antennas with 50 Ω input impedance will be very useful for quasi-optical power combining since they can be integrated directly with off-the-shelf MMICs without any matching network. This advantage has been demonstrated in a 4x4 16-element quasi-optical amplifier array which was constructed by bonding typical MMIC amplifier blocks between two five-slot antennas[2].

IV. Conclusions

A variety of cpw-fed folded- and multiple-slot antennas on thin substrates have been explored using the FDTD technique with PML ABC in this paper. Simulations compare quite well with measurements. Future work will include applying these results to the design of a broadband quasi-optical HBT amplifier array at U-band.

V. Acknowledgments

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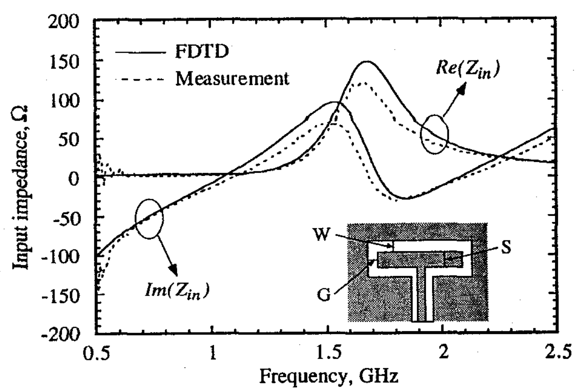

Figure 1 — Measured and calculated input impedance of the folded-slot antenna on 0.813 mm Duroid 5880 substrate with ε_r=2.2.

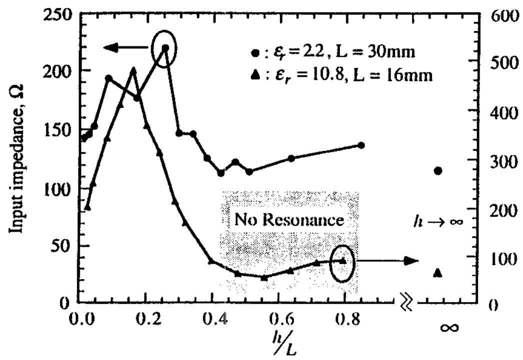

Figure 2 : Input impedance at resonance versus substrate thickness for both $\varepsilon_r = 2.2$ and $\varepsilon_r = 10.8$. In the shaded region, there is no resonance from simulation for $\varepsilon_r = 10.8$ case. For all data points, L is equal to 30mm and 16mm for $\varepsilon_r = 2.2$ and $\varepsilon_r = 10.8$ respectively.

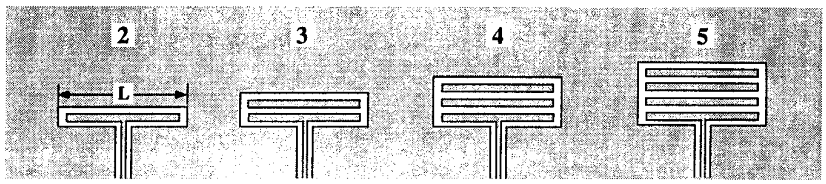

Figure 3 : Drawings of two-, three-, four-, and five-slot antennas. The dimensions of these antennas are : L = 7.2 mm, W = S = G = 0.3 mm.

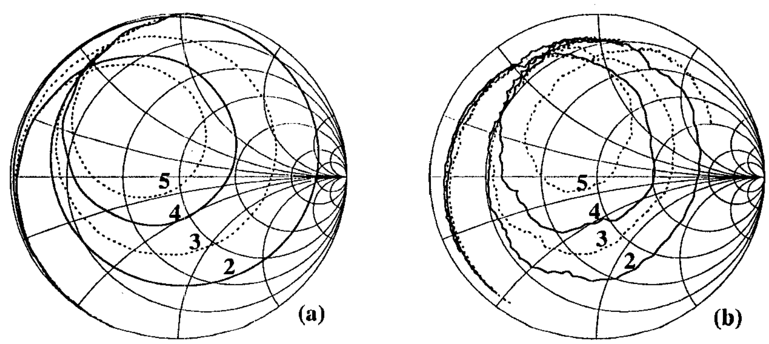

Figure 4 : Illustration of impedance scaling with the number of slots for 0.635 mm Alumina substrate for resonant frequency near 10 GHz. (a) simulation. (b) measured results. The frequency range is from 5 GHz to 15 GHz.