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2D PIM Simulation Based on COMSOL

**Xinbo Wang[1], Wanzhao Cui[1], Jingyu Wang[2, 3], Jingnan Pan[2], Xiaocheng Zheng[2],
Jiangtao Huangfu[2], and Lixin Ran[2]**

[1]National Key Lab of Science and Technology on Space Microwave Technology
Xi'an 710000, China
[2]Department of Information and Electronic Engineering, Zhejiang University
Hangzhou 310027, China
[3]Department of Photonics Engineering, Technical University of Denmark
Copenhagen, DK-2800, Denmark

Abstract— Passive intermodulation (PIM) is a problematic type of nonlinear distortion encountered in many communication systems. To analyze the PIM distortion resulting from material nonlinearity, a 2D PIM simulation method based on COMSOL is proposed in this paper. As an example, a rectangular waveguide filled with nonlinear dielectric was taken. Both of the effect of nonlinear coefficients and geometrical discontinuities were taken into consideration. The contribution of this paper is to make the PIM simulation more convenient, especially for those who are not good at analytical methods, and those who are not familiar with computational techniques. This type of analysis will aid in the development of PIM prediction, as well as PIM mitigation in the future.

1. INTRODUCTION

PIM is notoriously known for its detrimental effect on performance of base stations used in the space, military and civil telecommunications. PIM products, resulting from passive nonlinearities, occur in the reception band of antenna and degrade the system signal integrity. There are basically two types of passive nonlinearities, namely the contact nonlinearities and the material nonlinearities. In recent years, more and more efforts have been devoted to the study on the latter one, which refers the bulk materials, such as ferromagnetic materials and carbon fibers, that have nonlinear electrical characteristics [1–4]. Not only the prediction of PIM generation on printed transmission lines has been reported in [1], but also a PIM mitigation method by adding controlled thicknesses of nickel and gold plating to the conductors of a coaxial line, has been proposed in [4].

Although analytical methods have been widely used in these studies, they provided limited discussion for a specific shape of passive devices. If geometric effects are taken into account, the analytical result may not be obtained any longer. In that case, numerical simulation is more attractive. Both of Finite Element Method (FEM) and Finite-Difference Time-Domain (FDTD) are good candidates for such problems. In [5], codes based on FEM were developed to evaluate nonlinear line resistance and inductance of the microstrip lines. While in [6], a modified FDTD method involving current-mode nonlinearity is proposed, and its validity was confirmed through an experiment using the open-ended coaxial method.

However, both of the methods above require a good comprehension of computational electromagnetics, which is a little bit difficult for many engineers in passive device design. In this paper, the well-known commercial software COMSOL Multiphysics is employed for the PIM simulation. Those who are not familiar with computational techniques, but have a solid background in electromagnetics should find it extremely beneficial. The contribution of this paper is to make the PIM simulation more convenient. And this type of analysis should aid in the development of PIM prediction, as well as PIM mitigation.

2. PROBLEM FORMULATION

Maxwell equations are fundamental laws governing the behavior of a electromagnetic field in media. However, they do not contain information about the material properties. To characterize material properties, the so-called constitutive relations should be introduced as a necessary supplement. Constitutive relations in the most general form can be written as

$$\begin{bmatrix} c\bar{D} \\ \bar{H} \end{bmatrix} = \bar{\bar{C}} \cdot \begin{bmatrix} \bar{E} \\ c\bar{B} \end{bmatrix} \tag{1}$$

where c is the velocity of light, and $\bar{\bar{C}}$ is a constitutive matrix.

According to the functional dependence of $\bar{\bar{C}}$, the media can be classified as nonlinear, if $\bar{\bar{C}}$ is a function of the electromagnetic field strengths [7]. This relation can be very complicated in real world. As an simple example, the relation in [8] is taken in this paper, which satisfies the equations below,

$$\bar{B} = \mu_0 \bar{H} \tag{2}$$
$$\bar{D} = \varepsilon_r \varepsilon_0 \bar{E} + \bar{D}_r \tag{3}$$

where $\bar{D}_r = \chi \varepsilon_0 (E_x^2, E_y^2, E_z^2)^T$, is the nonlinear component of electrical displacement, and χ is the nonlinear coefficients.

Maxwell equations, accomplished with constitutive relations, play a central role in the analysis of nonlinear electromagnetic problems. Under certain circumstances, it can be helpful to formulate the problems in terms of the vector potential $\bar{A}$ and scalar potential Φ. They are given by the equalities

$$\bar{B} = \nabla \times \bar{A} \tag{4}$$
$$\bar{E} = -\nabla \Phi - \frac{\partial \bar{A}}{\partial t} \tag{5}$$

The defining equation for the magnetic vector potential is a direct consequence of the the magnetic Gauss's law, while the electric scalar potential results from Faraday's law.

The potentials would be somehow arbitrary without the Lorenz gauge condition as an additional restriction.

$$\nabla \cdot \bar{A} + \varepsilon_r \varepsilon_0 \mu_0 \frac{\partial \Phi}{\partial t} = 0 \tag{6}$$

Taking all the equations from Eq. (2) to Eq. (6) into account, a wave equation can be derived from Maxwell equations,

$$\varepsilon_r \varepsilon_0 \mu_0 \frac{\partial^2 \bar{A}}{\partial t^2} - \mu_0 \frac{\partial}{\partial t} \bar{D}_r + \nabla \times (\nabla \times \bar{A}) = 0 \tag{7}$$

The main idea of PIM simulaiton is to solve the partial differential equation in Eq. (7), accomplished with proper boundary conditions. In the next section, the well-known commercial FEM software COMSOL Multiphysics is employed to solve it.

3. SIMULATION AND RESULTS

COMSOL Multiphysics is an excellent, state-of-the-art software for the solution of many types of partial differential equations, both stationary and time-dependent, by numerical techniques based on the finite element method. In this section, a rectangular waveguide filled with nonlinear dielectric is analyzed by COMSOL.

Consider a metallic rectangular waveguide having dimensions b along the z axis, and $a > b$ along the y axis. The TE fields, where the electric field is along the z axis only, were investigated. When $a = 100\,\text{mm}$ and $b = 30\,\text{mm}$, the cutoff frequency of TE_{10} and TE_{01} mode are $1.5\,\text{GHz}$ and $5\,\text{GHz}$, respectively.

Although the waveguide is 3D in reality, as shown in Fig. 1(a). It is sufficient to solve an equivalent 2D problem in Fig. 1(b), because the fields have nothing changes along the z axis. Besides, modeling in 2D usually brings two advantages: (a) 2D models are easier to modify and solve; and (b) Given that the necessary approximations are small, the solution will be more accurate in 2D, because the mesh is much denser.

To introduce nonlinear dielectric inside the waveguide, the electromagnetic properties of the sub domain is configured so that it satisfies the nonlinear constitutive relation in Eq. (2) and Eq. (3), as shown in Fig. 2.

The next step is to determine the 4 boundaries in this model. Assuming that the electromagnetic wave propagates in the x direction, and B1 is the input port, while B4 is the output one. The other two boundaries are Perfect Electric Conductor (PEC) for the metallic waveguide. In order to make TE_{10} the only mode in the waveguide, the excitation signal on input port is known analytically to be

$$E_{z0} = \sin \frac{\pi(a - y)}{2a} (\cos 2\pi f_1 t + \cos 2\pi f_2 t) \tag{8}$$
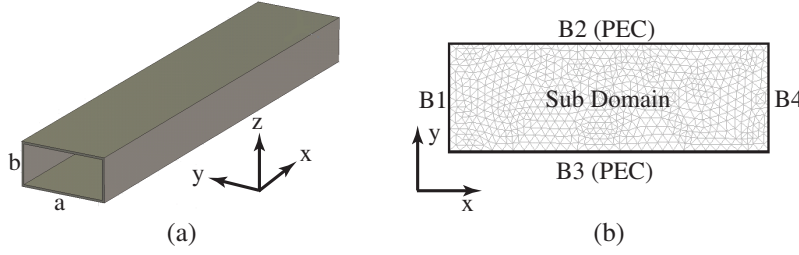
Figure 1: Waveguide model in the simulation: (a) waveguide in 3D; (b) equivalent 2D model.
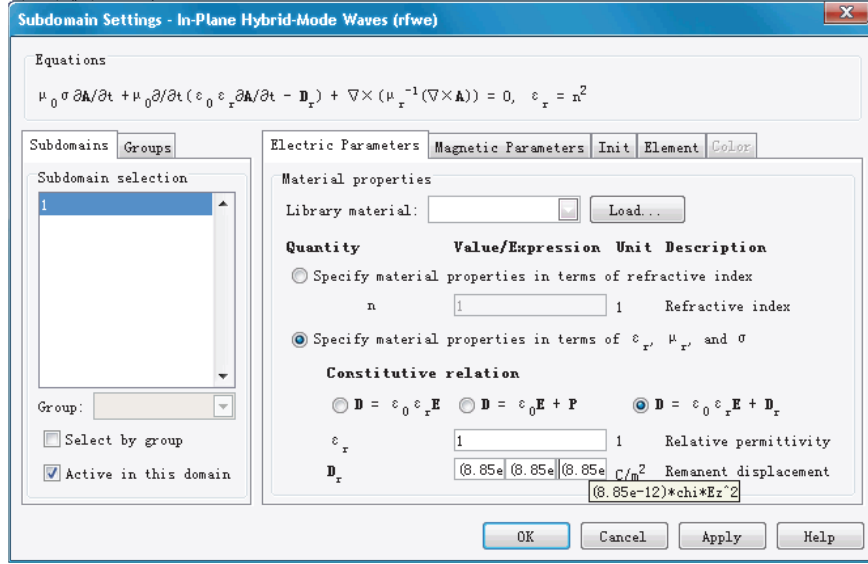

Figure 2: Electromagnetic properties configuration of sub domain.

where $f_1 = 2\,\text{GHz}$ and $f_2 = 3\,\text{GHz}$, are the frequencies of the 2 input carriers, respectively.

A transient simulation in time domain has been used to evaluate the PIM distortion in the waveguide. In order to achieve enough frequency resolution, the simulation time has been configured to be as long as $2 \times 10^{-8}\,\text{s}$. And the time step was $2 \times 10^{-11}\,\text{s}$, so that it satisfied the requirements of Nyquist-Shannon sampling theorem. After the field simulation, COMSOL script has been used for post-processing. The basic idea is to monitor the electric field strength at the output first, and the time-domain signal is then converted into the frequency domain by performing a Fast Fourier Transform (FFT).

The spectrums of the output signals with different nonlinear coefficients χ are shown in Fig. 3. The first curve $(\chi = 0)$, which means the media inside the waveguide is totally linear, was used for comparison. Because the nonlinearity inside the passive device is believed to be very weak, all the χ used in the simulation were less than 0.1. It is obvious that the 3rd order products PIM3 $(2f_2 - f_1 = 4\,\text{GHz})$ appeared, if $\chi \neq 0$. And its amplitude increased, as χ got larger.

Further more, a waveguide with specific geometry has been investigated, as shown in Fig. 4(a). This type of waveguide changes the direction of the $\bar{H}$ field components, while leaves the direction of the $\bar{E}$ field unchanged. So it is called an H-bend. Unlike the normal waveguide, the bend will introduce unavoidable losses in signal power because of the unwanted reflections. Fortunately, these reflections can be minimized by keeping the bend smooth with a large enough radius. The H-bend was assumed to be full filled with nonlinear media of $\chi = 0.05$. And a normal waveguide with the same nonlinear media and the same length has also been simulated. Fig. 4(b) is the output spectrums of the these two kinds of waveguides. Given that all the other conditions were the same, the differences in spectrum is believed to result from the geometric effects. To the best of our knowledge, there are limited investigations on PIM analysis of specific geometry in literature at present. Development of the rigorous electromagnetic phenomenology of PIM generation in passive device with geometric effects remains an extremely challenging task. And the method proposed in this paper is a good candidate to solve such problems. Its validity will be confirmed through experiments in the future.
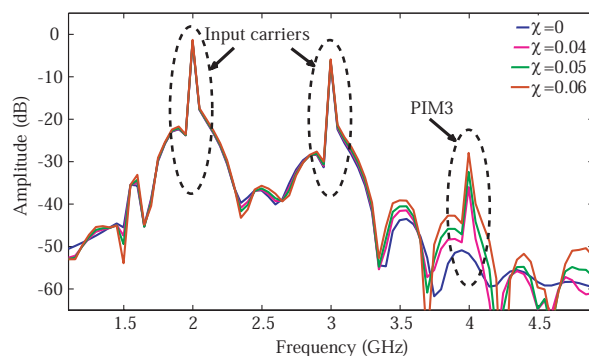
Figure 3: The spectrums of the output signals with different nonlinear coefficients.
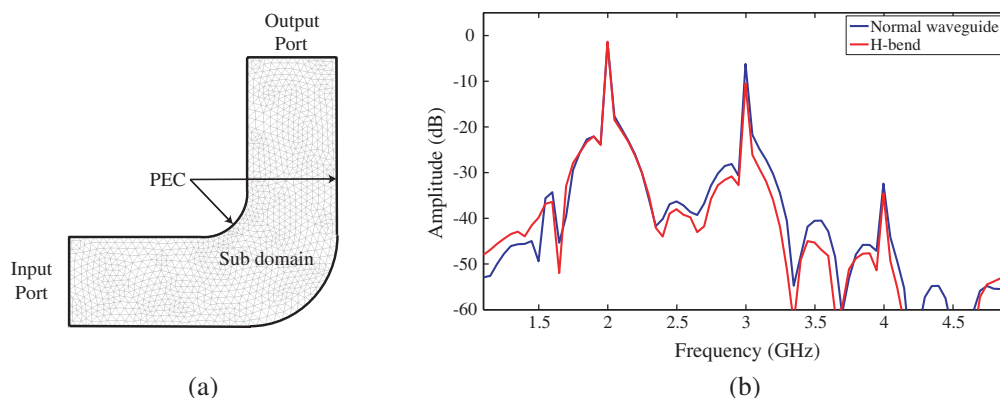

(a)   (b)

Figure 4: Simulation of waveguide with specific geometry: (a) 2D model of H-bend; (b) output spectrums.

4. CONCLUSION

A PIM simulation method based on commercial software is proposed in this paper. It is helpful in the analysis of PIM distortion resulting from material nonlinearities. Not only the effects of nonlinear coefficients, but also the geometrical discontinuities, have been investigated. This method should aid in the development of PIM prediction, as well as PIM mitigation. The further research will focus on the effective determination methods for nonlinear coefficients. In addition, a system level simulation is also on the schedule.

ACKNOWLEDGMENT

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