FDTD Simulation of an Electromagnetic Bandgap Structure with Waveguiding Defect at Microwave Frequencies

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***Abstract*— Finite Difference Time Domain (FDTD) is one of the most widely used techniques today employed in both academia and industry to study different structures. In this project report, we report the 2D Finite Difference Time Domain (FDTD) simulation results of an electromagnetic bandgap structure with a waveguiding defect at microwave frequencies. The structure could effectively be used as a bandpass waveguide operating at a central frequency of 10 GHz. Moreover, it can be employed for wireless interconnect purposes, where the data rate levels require to preserve the integrity of the signal while providing high data throughput are on the orders of tenths of GHz. Our simulation results show that the waveguide structure indeed could be used a bandpass waveguide. The power transmission spectra depict a 10 GHz central frequency achieving bandwidth of around 80%, over which the transmission spectra present an excellent gain flatness and sharp stopband. The structure can potentially be scaled to operate in other frequency ranges by merely tweaking the geometry of the structure.**

***Index Terms*—Finite-difference time-domain (FDTD), band-gap structures, wireless interconnects, waveguides**

I. Introduction

IN the last several years, various types of periodic structures such as electromagnetic bandgap structures (EBGs) and defect ground structures (DGSs) etc. [1] – [7] have been a widely researched topic, and they have generated significant interests in applications for microwave and millimeter-wave circuits and devices design. For example, a planar periodic structure called high-impedance ground structure, has been proposed and used to improve antenna performance [2], on the other hand a compact EBG structure named the uniplanar compact EBG (UC-EBG) was realized with periodic metal pads etched on ground plane connected by narrow lines to form a distributed LC network [1], [6], [7]. Likewise, we also have planar periodic structures such as compact coplanar waveguide (CPW) periodic structures that have been used to realize high performance filters or to reduce harmonic effects in power amplifiers and to suppress leakage in CB-CPWs [4], [5] – [7].

These applications only became possible since the periodic structures exhibit excellent band stop characteristics. So, we can see that with EBG structures the possibilities are endless from an application specific point of view, and it would continue to grow in the years to come.

On similar lines, millimeter wave communications have also gained quite a lot of attention for communication applications [1]. The primary reason for this could be due to the number of interesting features of THz waves, including the tens and hundreds of gigahertz bandwidths available. The luxury of having higher data bit rates allows the users to have more resources and applications aiming to provide a better user experience [2]. However, this trend comes with several other technical challenges that needs to be attacked and solved first or even be understood in its entirety before its development, for instance, these systems should be able to provide interconnects that supports the high level of data rates while preserving the integrity of the signal [3] – [4]. The feasibility to provide a wireless interconnect band pass had already been demonstrated in [2], by using a periodic structure with an introduced line defect, obtaining as a result, what we call as well as described in the first part of this section, an Electromagnetic Band Gap structure [5]. In the structure reported in [3], the waveguide has a wide bandwidth with a central frequency around 10 GHz, and potentially can handle very high data bit rates while maintaining its signal integrity.

Our main aim in this paper is to validate the functionality of the structure with the help of 2D FDTD computational simulation. The use of a 3D FDTD over 2D FDTD would un-arguably yield us a more accurate result but even with a 2D FDTD approach we could validate the results with a recommendable level of accuracy while at the same time reducing ourselves with the time and memory cost of our computations.

A detailed description of the geometry of the structure as well as the electric parameters used in our numerical simulations has been described in Section II of this project report. The simulations results obtained through this method has been discussed in Section III. Finally, the conclusion of our simulation results has been presented in Section IV of this project report.

II. Model Description

In this section, we are going to describe the geometry of the structure used in the simulations and follow it up with a discussion on the electrical parameters. Finally, towards the end of this section, we are going to introduce and discuss about the source and the receiver model which we have taken up in our FDTD simulation based study of the wireless interconnect waveguide.

A. Structure Geometry

In the simulations that we did, we had employed the standard FDTD method implemented on a uniform 2-D Cartesian grid [7]. This cell size was found to yield numerically converging results relative to rendering the geometry of the array of metal pins comprising the EBG structure [1]. The structure which was taken up in this study corresponds to a bandpass waveguide that effectively operates with a central frequency of 10 GHz. The bandpass waveguide operates with a wide bandwidth of approximately 8.7 GHz, in which we define the usable bandwidth to be the frequency range over which the magnitude of the power transmission variation does not exceed 1dB.

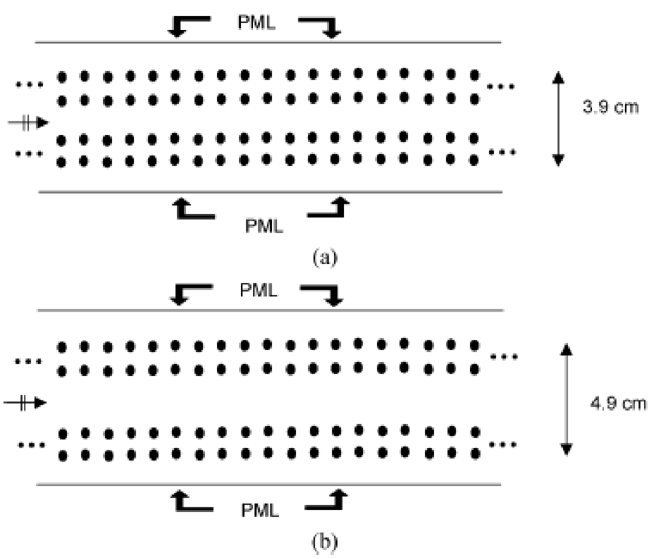

Fig. 1: Waveguiding defects embedded within the square EBG structure of metal pins of Fig. 1. (a) Single-row defect created by removing one row of pins from a structure having initially five rows of pins and (b) double-row defect created by removing two rows of pins from a structure having initially six rows of pins. **(The following figure was taken from Reference [1])**

Our structure was a periodic array of vias with linear defects as shown in Fig. 1. If we look closely, we would see that the structure had a double arrow defect which had been intentionally created by removing the central rows of a periodic 6 row unit cell. Now, the overall lateral dimensions of the structure were kept at 4.9 cm. Moreover, the excitation signal was modeled with a resistor voltage source located to the left side of the structure. The structure had a total length of about 10 cm between the input and output probes. The radius of the vias was set to 0.83 mm and the center to center separation between vias was 4.6mm. The waveguide is bounded with a double-sided circuit board having a thickness of 3.2mm. Since the vias (copper cylinders) will do a good job of confining the energy, and because the dielectric is lossy, for simplicity we used the regular 2-D FDTD (no split fields or PML) with simple PEC boundaries. Now, that the geometry is perfectly defined we proceed with the next step i.e. defining the electrical parameters.

B. Electrical parameters

Principally, the dielectric defined for the waveguide between the ground planes follows the parameters of a standard FR4 substrate with a relative dielectric constant of 4.3. The loss tangent values were assumed to be constant over the range of frequencies analyzed and set to 0.017. Copper vias were used to effectively model the pins of the structure as described in section II of this project report. In the numerical simulations, the conductivity of the copper regions was set to $5.96\ X\ 10^7 [S/m]$. Moreover, the conductivity of copper was assumed to be frequency independent, which was a reasonable approximation to make considering the range of frequencies taken up in this study. Finally, we can now discuss about our source and receiver model in the next sub-section.

C. Source and Receiver Model

The excitation wave was modeled with a resistive voltage source having a $50\,\Omega$ characteristic impedance. In our simulations, the resistance was taken in into account by modifying the update coefficients of the electric field at the position of the source via, as described in [1]. For the source waveform, we used Gaussian modulated a sinusoidal signal whose mathematical characterization is of the following form:

$$S = \sin\omega_0 t \ \ e^{-\left(\frac{t-t_0}{t_h}\right)^2}$$

here ω_0 denotes the central frequency, t_0 is the delay time and t_h is the width of our gaussian pulse. By changing, $t_0$and t_h it is possible to adjust the bandwidth of the frequency spectrum of the waveform.

In the same way, the receiver was modeled with a shape of a via having a characteristic impedance of $50\,\Omega$. Having described the structural geometry, electrical parameters as well as the source and receiver models, we can now proceed with the simulations using 2D FDTD.

III. Simulation Results

In this section, we are going to describe at first the details of the simulation setup, and follow it up summarizing the results that we obtained. We would also try to provide a description of the physical significance of our results.

A. Simulation Setup.

In our simulation setup, the time steps in the simulations was set around the Courant Limit for a 2D FDTD model. Again, as we had already pointed out in section II, for simplicity we used the regular 2-D FDTD (no split fields or PML) with simple PEC boundaries. The unit cell grid was set up in such a way, that there were at least 4 unit cells covering each via, in this case this corresponds to a grid cell of approximately 2mm. We applied 2-D FDTD modeling to calculate for each waveguiding defect the magnitude and phase of the electric field transmission characteristic over a longitudinal span along the center axis of the waveguide. Our main aim here was to define the usable transmission bandwidth as the frequency span over which the transmission magnitude variations are less than 1 dB. As described in [1] we also tried to examine the possibility of multimoding [6], wherein we performed simulations that offset the source distribution in the transverse direction. As already stated in [1], our simulations too indicated little (if any) evidence of odd-mode generation.

B. Simulation results.

In this sub-section, we are going to focus only on interpreting the significance of our simulation results. In fig. 2, the time domain electric field waveform of the modeled source has been depicted. It was excited at the resistive voltage source point for an assumed 24 ns (full width half maximum) and transmitted 10 GHz carrier pulse having a Gaussian envelope. The center frequency was set to 10 GHz. The delay time was set in such a way, that the wave form would start at $n_0 = 120$ time steps. Furthermore, the Gaussian pulse width was set to

$$n_{half} = 3 * n_0$$

allowing the waveform to start and decay smoothly in the range of our frequency of interest. To provide evidence to our statement, this is better observed in fig. 3 where we effectively show the corresponding frequency spectrum of the excited source. In the frequency spectrum plot, we could see that the full width half maximum of the gaussian envelope is adjusted such that the signal smoothly vanishes between 2GHz and 18 GHz.

The time domain electric field time waveforms at the source is shown in fig. 4 where it is possible to observe that it resembles the original waveform excited by the source. Fig. 5 shows the corresponding spectra of the electric field at the source point where again it clearly shows that the central frequency of the waveform is effectively 10 GHz, and it smoothly decays in the region of our frequency of interest. An important thing to note here is that there is some degradation around the center frequency i.e. 10 GHz but this is due to the intrinsic accuracy of the method used, and bears no real physical significance as such.

Now coming to the receiver side, the electric field was effectively measured at the center of the via. Correspondingly, the time domain electric field of the waveform is depicted in fig.6, where it is possible for us to see that the effects of the waveguide on the original waveform is pretty much visible, i.e. maintaining most of the power around the central frequency as shown in the frequency spectrum plot of fig. 7. As it is observed here, that the bandwidth of this signal now behaves more of like a passband.

Fig. 8 is simply a plot of the gaussian pulse propagating down the waveguide i.e. a snapshot in time of the pulse when it is about halfway-down the waveguide.

Finally, the transmission spectra of the simulation model were calculated by taking the ratio of the electric field at the receiver point to the electric field at the excited point. The simulation result for the power transmission spectra has been plotted in fig. 9. The transmission spectra have a few interesting things which needs to be discussed. Firstly, the transmission spectra show a strong sharp transition at around 6 GHz followed by a flat response with a central frequency of 10 GHz. Secondly, we can also see that the stopband of the spectrum is located around 14 GHz. Thirdly, it is also quite evident from the plot that the bandwidth of the structure is approximately 8 GHz, equivalent to 80% usable bandwidth.

The simulation results which we have obtained using a 2D FDTD approach is in very close agreement with simulation and experimental results as discussed in [1]. The differences which we observed in your 2-D results vs. the published 3-D results as in [1] are: our transmission ratio is about 5 dB lower than the one reported in [1] and it exhibits some minor wiggles in the passband which is due to the intrinsic accuracy of the method used.

IV. Conclusions

In conclusion we can say, that in this project report we could effectively model an electromagnetic bandgap structure with waveguiding defect at microwave frequencies and provide evidence that it could potentially be used as a wireless interconnect bandpass waveguide. It essentially means that there is feasibility on the use of a wireless interconnect technology band pass for high speed digital circuits by introducing defect on the periodic structure.

Moreover, the simulation results show that it is possible to obtain a bandwidth of 80% for a 10GHz central frequency which was our frequency of interest from the start. As described in [1], the very same structures when scaled to millimeter-wave center frequencies like, say for example, above 300 GHz, these kinds of wireless interconnects which have been studied in this project should be feasible of supporting data rates in the range of hundreds of Gb/s, assuming the availability of suitable low-loss dielectrics.

However, as discussed in [3] – [4], one of the challenges in the design at such higher frequencies is that the permittivity and conductivity start to get into the picture and tend to exhibit very strong dependence on frequency. In our model, we have assumed a constant permittivity and loss tangent for the dielectric, as well as a simple constant conductivity value for the copper vias. Now, to account for the effect of permittivity and conductivity, the layers of the structure can be modeled with a Drude-like dispersion model. Moreover, the losses at higher frequencies in standard substrates used at microwaves become more evident. Despite such challenges, this approach has been demonstrated in [8], where the authors have scaled down the structure to have a central frequency of 50 GHz.

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FIGURES

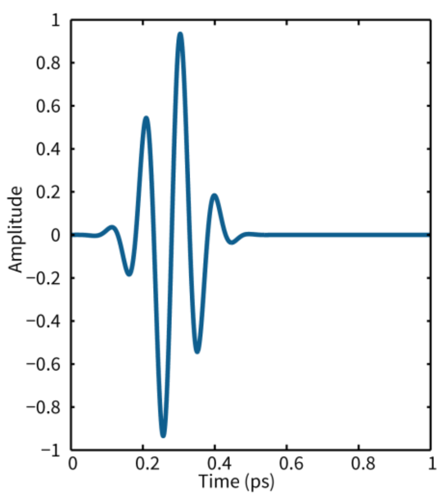

Fig. 2 The time domain source waveform

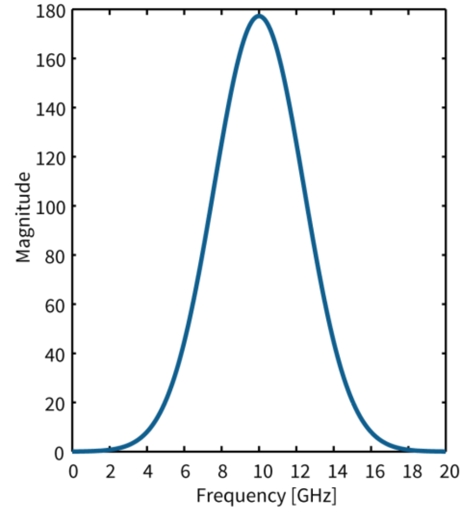

Fig. 3 The spectrum of the source waveform

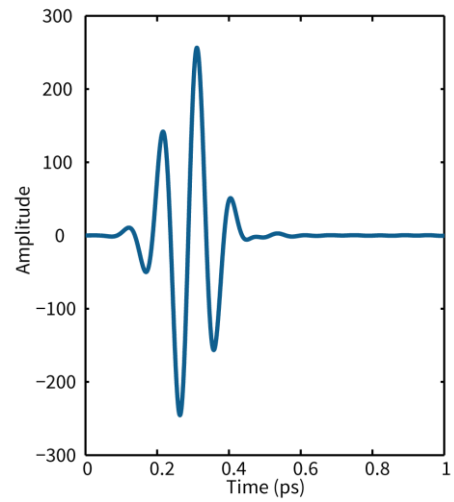

Fig. 4 The time-domain electric field waveform sampled at the source location

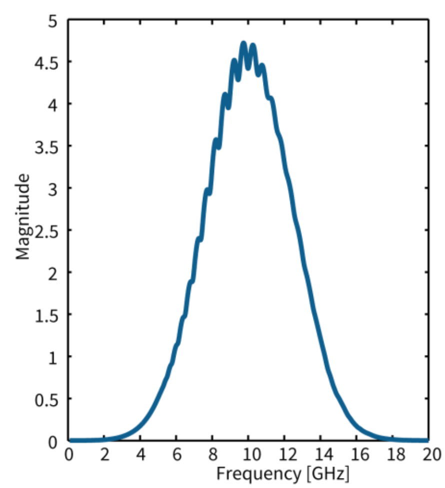

Fig. 5 The spectrum of the time-domain electric field waveform sampled at the source location

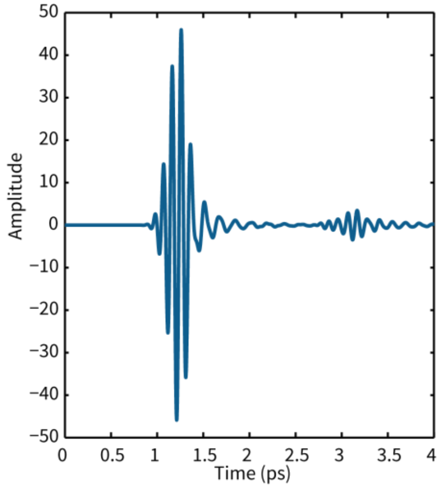

Fig. 6 The time-domain electric field waveform sampled at the center of the receiver

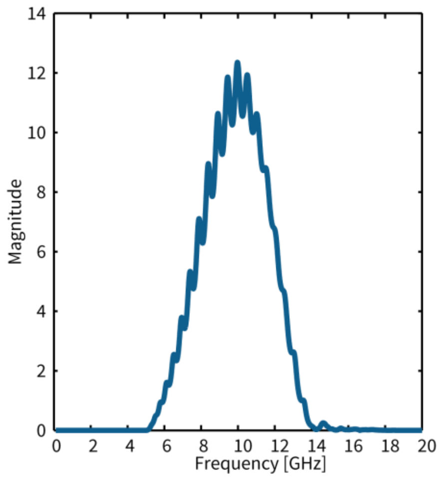

Fig. 7 The spectrum of the time-domain electric field waveform sampled at the center of the receiver

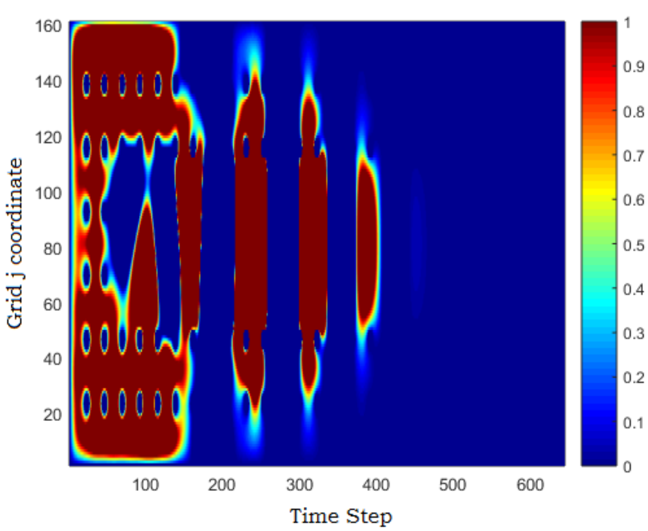

Fig. 8 The gaussian pulse propagating down the waveguide (a snapshot in time of the pulse when it is about halfway-down the waveguide).

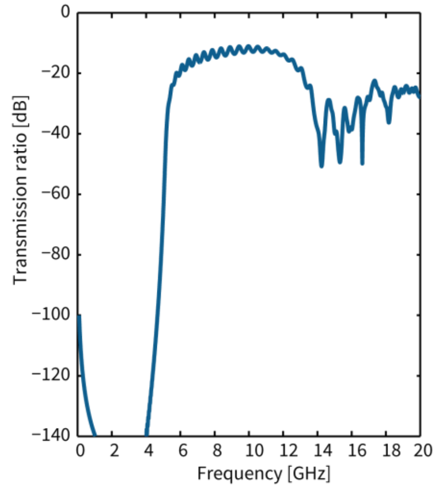

Fig. 9 Power transmission spectra for the waveguide