Volume 3, Issue 3, 2020 ISSN: 2664-0821
DOI: https://doi.org/10.31058/j.ap.2020.33003

Simulation of Finite Difference Method-based Electromagnetic Field on Gallium Nitrite Material for Photodetector Design

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Received: 25 May 2020**; Accepted:** 1 June 2020**; Published:** 4 June 2020

Abstract:

The paper mainly focuses on finite difference method with time domain for simulation of electromagnetic field on Gallium Nitrite material for photodetector design. At first, the interface between air and Gallium Nitrite has to be considered for analyzing the finite difference method to obtain the phonon condition exactly. The transmission and reflection waves could be detected from the observation point of the specific location. The boundary condition has to be specified in the test-bed environment. The perfectly match layer boundary condition is appropriate for implementation of the system. Based on the results from the simulation works, the condition for phonon control shall be defined for the application of photodetector purposes.

Keywords:

Finite Difference Method, Electromagnetic Field, Photodetector Design, Transmission and Reflection Waves

1. Introduction

Two-dimensional planar periodic structures find many applications in practice because of their spatial filtering characteristics. Gallium Nitrites (GALLIUM NITRITEs) consist of periodic arrangements of dielectric (or metallic) elements with a strong dielectric contrast [1]. In these structures, the achieved wavelength-scale periodicity affects the properties of photons in a way similar to that in which Gallium Nitrite crystals affect the properties of electrons. Light propagation along particular directions is forbidden within relatively large energy bands known as photonic bandgaps (PBGs) [2] in analogy with the concept of electronic bandgap in Gallium Nitrites. Initially proposed as a generalization of 1-D dielectric Bragg mirrors to two or three directions [3], Gallium Nitrites have opened new ways to tailor the light–matter interaction and in particular to control spontaneous emission [4].

An efficient method to couple terahertz waves from a dielectric medium into a two-dimensional Gallium Nitrite is presented. The design parameters of the Gallium Nitrite interface to minimize reflection can be optimized using the conventional

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antireflection coating theory and the finite-difference time-domain simulations. The transmission spectra of a terahertz Gallium Nitrite with and without the optimization of the crystal interface were investigated [5]. It is shown that the transmission of the specific terahertz wave of interest can be significantly improved through the optimization of the Gallium Nitrite interface [6,7,8].

The paper is organized as follows. Section II states the experimental model of the test-bed. Section III presents the analysis on implementation. Section VI mentions the simulation results and discussions on that. Section V concludes the story of works.

2. Background Theory

When a light beam is normally incident from region 1 onto region 2which is placed between two semi-infinite homogenous media (region 1 and 3) as shown in Fig. 1, the reflectance of the incident light becomes zero when the following two conditions are satisfied simultaneously [9,10]:

$$|r_{12}|=|r_{23}| \tag{1}$$

And

$$e^{i(2\beta+\delta_{23}-\delta_{12})}=-1 \tag{2}$$

where r_{ij} and δ_{ij} correspond to the amplitude and the phase factor of the reflection coefficient of light propagating from region i to j, respectively. In this simple case, the optimal antireflection parameters, the refractive index $n_2=\sqrt{n_1 n_3}$ and the optical thickness $h = \lambda / 4$, are easily obtained from Eqs. (1) and (2) by using the reflection coefficients given by the Fresnel equations [11,12].

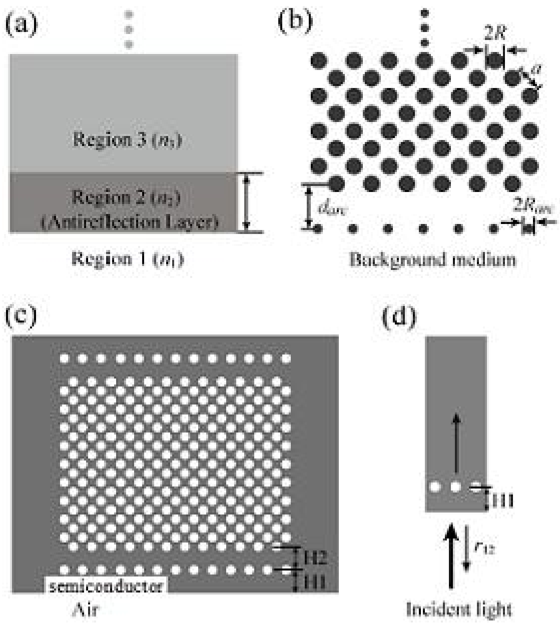

Figure 1. *(a) In the conventional 1D case, the antireflection parameters are the refractive index n_2 and the thickness h of an antireflection layer. (b) Antireflection parameters are the radius of rods or holes R_{arc} and the distance d_{arc} between the antireflection structure and the crystal truncation. (c) Antireflection parameters are distance H_1 and H_2. (d) Reflection coefficient r_{12} is a function of H_1.*

In this work, the antireflection parameters, H_1 and H_2 of Figure 1(c), to minimize the reflection at the interfaces between a hole-type Gallium Nitrite material and a

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outside dielectric were introduced. These design parameters can be optimized by the finite difference method with time domain simulations as described in [13], provided that r_{ij} are properly modified. In this analysis, r_{23} is the reflection coefficient of the semi-infinite Gallium Nitrite when the light is incident upon it from Gallium Nitrite, and r_{12} is that of the interface between Gallium Nitrite and air when the light propagates from air to the Gallium Nitrite, as shown in Figure 1 (d). Note that, the reflection coefficient r_{12} is a function of the design parameter H_1 [14,15,16].

3. Finite Difference Method

Finite-Difference method is a recognized practice for the investigation of semiconductor devices in semiconductor technology for research purposes [17,18].

That practice can solve a discretized Schrödinger equation in an iterative progression. Nevertheless, the technique offers only a second-order exact numerical clarification and needs that the spatial grid size and time step should convince a very limited condition in order to avert the numerical clarification from diverging. The details description on finite difference technique is discussed in the following sections. The approximating the time derivatives is given.

An intuitive first guess at approximating the time derivatives in Maxwell's Equation is

$$\nabla\times\bar{E}(t)=-\mu\frac{\partial\bar{H}(t)}{\partial t}\Rightarrow\nabla\times\bar{E}(t)\cong-\mu\frac{\bar{H}(t+\Delta t)-\bar{H}(t)}{\Delta t} \tag{3}$$

$$\nabla\times\bar{H}(t)=\varepsilon\frac{\partial\bar{E}(t)}{\partial t}\Rightarrow\nabla\times\bar{H}(t)\cong\varepsilon\frac{\bar{E}(t+\Delta t)-\bar{E}(t)}{\Delta t} \tag{4}$$

We adjust the finite difference equations so that each term exists at the same point in time.

$$\nabla\times\bar{E}(t)=-\mu\frac{\partial\bar{H}(t)}{\partial t}\Rightarrow\nabla\times\bar{E}(t)=-\mu\frac{\bar{H}\left(t+\frac{\Delta t}{2}\right)-\bar{H}\left(t-\frac{\Delta t}{2}\right)}{\Delta t} \tag{5}$$

$$\nabla\times\bar{H}(t)=\varepsilon\frac{\partial\bar{E}(t)}{\partial t}\Rightarrow\nabla\times\bar{H}\left(t+\frac{\Delta t}{2}\right)=\varepsilon\frac{\bar{E}(t+\Delta t)-\bar{E}(t)}{\Delta t} \tag{6}$$

These equations will get messy if we include interpolations.

We stagger E and H in time so that E exists at integer time steps (0, Δt, 2Δt,...) and H exists at half time steps (Δt/2, t+Δt/2, 2t+Δt/2,...)

$$\bar{H}\big|_{t+\frac{\Delta t}{2}}=\bar{H}\big|_{t-\frac{\Delta t}{2}}-\frac{\Delta t}{\mu}\left(\nabla\times\bar{E}\big|_{t}\right) \tag{7}$$

$$\bar{E}\big|_{t+\Delta t}=\bar{E}\big|_{t}+\frac{\Delta t}{\varepsilon}\left(\nabla\times\bar{H}\big|_{t+\frac{\Delta t}{2}}\right) \tag{8}$$

4. Analysis

To realize the effects of the interface optimization on the reflection of light beam, a Gallium Nitrite material which consists of air holes with the lattice constant a = 57 μm and hole radius r = 0.35a in Gallium Nitrite material were considered. However, to our knowledge, there has been no study on the self-collimated propagation of the THz wave. Hence, the reflection minimization of self-collimated beams at the Gallium Nitrite material interfaces was observed.

The source pulse started from 800 nm from the Gallium Nitrite material. When the pulse was reached the interface of the Gallium Nitrite material, the transmission and reflection waves would be observed from the Gallium Nitrite material.

Figure 2, Figure 3 and Figure 4 demonstrate the Result of Initial Source for Finite Difference Method on Gallium Nitrite Materials (T=0), (T=200) and (T=400) fs for time steps conditions.

The various time steps were completed after observing the source pulse by the finite difference method with time domain approaches. The boundary condition for the analysis is perfectly match layer and the transmission and reflection pulses could be detected by the observation points which was located at 200μm from the Gallium Nitrite material.

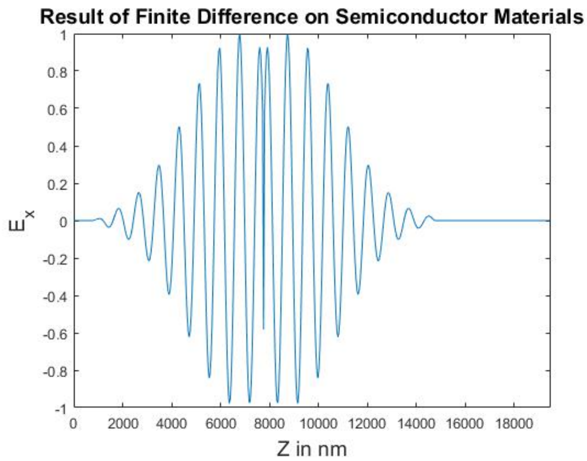

Figure 2. *Result of Initial Source for Finite Difference Method on Gallium Nitrite Materials (T=0).*

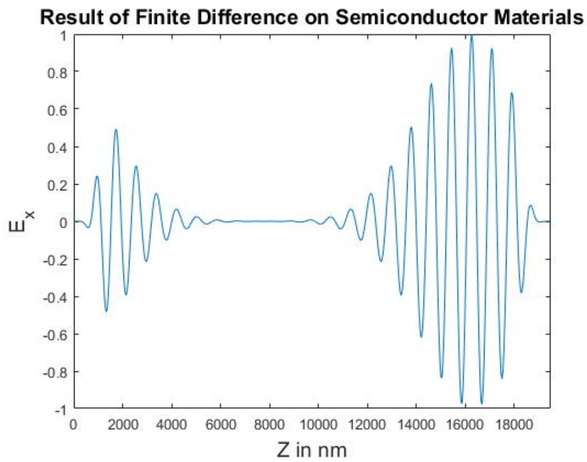

Figure 3. *Result of Initial Source for Finite Difference Method on Gallium Nitrite Materials (T=200).*

The observation on simulation results of higher time step could be proved with the zero reflection spectra from the Gallium Nitrite material. It means that the reflection pulse would be approached to zero value after the completion of simulation. Figure 5 shows the Result of Initial Source for Finite Difference Method on Gallium Nitrite Materials with Full Time Step. According to the simulation results, the phonon control could be carried out because of the definite reflection spectra of the interface of Gallium Nitrite material.

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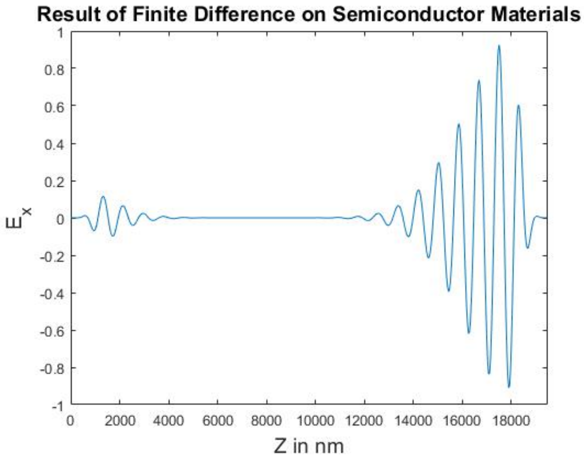

Figure 4. *Result of Initial Source for Finite Difference Method on Gallium Nitrite Materials (T=400).*

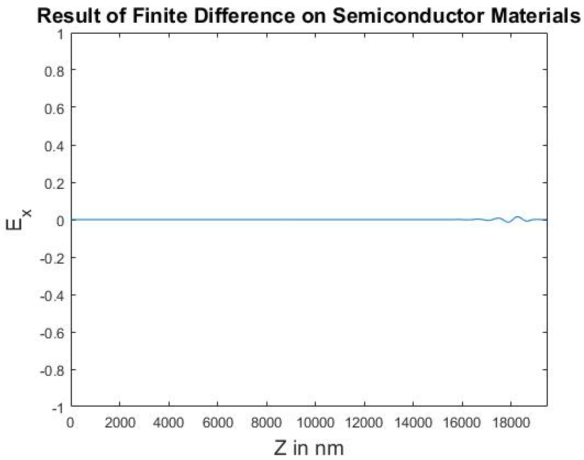

Figure 5. *Result of Initial Source for Finite Difference Method on Gallium Nitrite Materials with Full Time Step.*

5. Conclusions

It is theoretically shown that the transmission of the specific THz wave of interest can be significantly improved through the optimization of the Gallium Nitrite interface. While the finite difference method with time domain model used to predict the transmitted pulse was accurate, transmission spectroscopy for the detection is not practical because of the restrictions of observation placement and sample thickness. The results have shown that the EM transmission spectrum of the Gallium Nitrite material in the visible and infrared regions can be tuned simply by adjusting the thickness of the air gap between the two interface medium.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgment

The author would like to acknowledge many colleagues from the Department of Electronic Engineering of Yangon Technological University.

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