Terahertz Detection Using Electro-Optic Effect in a ZnTe Layered Structure

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Abstract— **In this work, a layered structure of ZnTe slabs separated by air-gaps is used to detect terahertz pulses. The structure which can be considered as a periodic structure is operating close to its stop-band edge where the transmission of the optical signal is attenuated. Applying the terahertz signal will vary the refractive index of the ZnTe slabs of the periodic structure due to the electro-optic effect in ZnTe. Consequently, the stop-band will shift in the presence of the terahertz signal. Hence, the intensity of the transmitted optical signal is modulated by the terahertz pulse, thus the terahertz signal can be detected. To examine the performance of the proposed detector, a finite-difference time-domain (FDTD) analysis is employed so that the nonlinear processes involved in the ZnTe slabs can be taken into account rigorously. Performance of the proposed structure will be compared with that of the conventional detectors based on a single ZnTe layer.**

Keywords- Terahertz detector, ZnTe slab, Electro optic effect, Optical modulation

I. INTRODUCTION

The terahertz frequency range (0.1- 10 THz) has been mainly used for spectrometery and astronomical applications [1] where detectors are commonly of the bolometer type operating in liquid helium temperature [2]. In the recent years, this frequency range has been considered for other applications such as imaging, medical diagnosis, and communications [3]-[5]. For some of these applications, detection at room temperature is desirable. Coherent detection methods commonly use photoconductive detection and electro-optic sampling [6], [7]. The advantage of using the latter over photoconductive detection is its wider operation bandwidth [8]. Since terahertz signals are finding their applications in a larger area, various methods of their detection are still being investigated by researchers.

In this research, a new method of terahertz detection using a layered structure of ZnTe slabs is proposed. This detector which is also based on the electro-optic effect of ZnTe detects a terahertz signal by measuring the variation in the intensity of an optical wave traversing the structure, simultaneously.

In Section II, the electro-optic effect in ZnTe is reviewed. Later, in Section III, the principle of terahertz detection in the proposed structure is discussed and the detector performance is analyzed using a FDTD method. Simulation results are presented in Section IV. Finally, a summary of the obtained results is presented in Section V.

II. ELECTRO-OPTIC EFFECT IN ZNTE

In a nonlinear medium with no temporal dispersion, a component of the electric field E_i is related to the corresponding component of the electric polarization vector P_i according to [9]

$$P_i(t) = \varepsilon_0 \left(\chi^{(1)} E_i(t) + \chi^{(2)} E_i^2(t) + \chi^{(3)} E_i^3(t) + ... \right) \quad (1)$$

where i refers to any of the three components of these vectors. Here, $\chi^{(1)}$ is the linear electric susceptibility whereas $\chi^{(2)}$ and $\chi^{(3)}$ are the second and third-order electric susceptibilities, respectively. The last two parameters lead to nonlinear effects. Usually, these coefficients have small values; hence, to benefit from the nonlinear effects, strong electric fields are required.
According to (1), the electro-optic effect is a change in the refractive index of a material in response to an electric field that varies slowly compared with the frequency of light. In ZnTe, the electro-optic effect is extremely fast such that a terahertz signal with the electric field E_{THz} can affect its refractive index. Generally, for a material showing the electro-optic effect, the refractive index can be expressed by

$$n = n_0 + \Delta n_1 + \Delta n_2 + ... \quad (2)$$

where n_0 is the linear refractive index of the material. In the presence of the terahertz electric field, the second and third terms in (2) are given by

$$\Delta n_1 = \frac{\chi^{(2)} E_{THz}}{n_0} \quad (3)$$

$$\Delta n_2 = \frac{3\chi^{(3)} \left| E_{THz} \right|^2}{2n_0} \quad (4)$$

which formulate the refractive index variation due to the Pockels and the Kerr effect, respectively. For ZnTe, the second and the third-order susceptibilities are $9\times10^{-11} \frac{m}{V}$ and $3\times10^{-19} \frac{m^2}{V^2}$, respectively [10]. Because of the typical

values for the terahertz electric field, only the second-order nonlinear polarization is considerable in ZnTe. Under this assumption, Eq. (1) is reduced to

$$P_i(t) = \varepsilon_0 \left(\chi^{(1)} E_i(t) + \chi^{(2)} E_i^2(t) \right) \quad (5)$$

Obviously, the refractive index of ZnTe at optical frequencies changes in response to the terahertz electric field. From (5), the refractive index of ZnTe slab is expressed by

$$n = (2\chi^{(2)} E_{THz} + n_o^2)^{1/2} \quad (6)$$

In the numerical simulations to follow, the amplitude of the terahertz and optical fields are selected to be $4\times10^7 \frac{V}{m}$ and $1\frac{V}{m}$, respectively. Moreover, n_0 is assumed to be 2.85 at the optical frequency and 3.178 at the terahertz frequency of our simulations [11].

III. Operation Principles of the Proposed Terahertz Detector

The configuration of the layered structure for terahertz detection is depicted in Figure 1 The structure is composed of ZnTe slabs and air gaps with a thickness of l and d, respectively. This structure is exposed to a terahertz pulse and a continuous sinusoidal wave at the optical frequency. The wavevectors of the incident waves are perpendicular to the structure surface as shown in Figure 1.

Presence of a terahertz pulse will change the refractive index of the ZnTe slabs at optical frequencies, as a result of which the stop-band of the periodic structure used in the proposed detector shifts. Now, if the working frequency is selected in the vicinity of the stop-band edges, the intensity of the transmitted optical signal is affected by the incident terahertz signal. Therefore, a conventional optical detector at the output of the structure will detect terahertz pulses with high sensitivity. The number of ZnTe slabs and also their thicknesses determine the optical output spectrum. Furthermore, one can design the proposed periodic structure to realize a modulation scheme of the incident optical signal. waves with the help of an optical detector.

IV. Simulation Results

For simulating the structure shown in Figure 1, one-dimensional FDTD method has been employed. The center frequency of the terahertz pulse and that of the optical wave are $10^{12}\,Hz$ and $3.8\times10^{14}\,Hz$, respectively. The terahertz pulse width is assumed to be 0.4×10^{-12} sec. The values of l and d are selected to be $0.5mm$ and $0.1mm$, respectively.

Figure 2 shows the effect of the terahertz pulse on the input optical signal. As can be seen from Figure 2, when the terahertz pulse traverses the structure, the intensity of the optical wave varies considerably. This variation of the optical wave amplitude is detectable by a conventional optical detector. Hence, the proposed structure can be used to detect terahertz waves with the help of an optical detector.

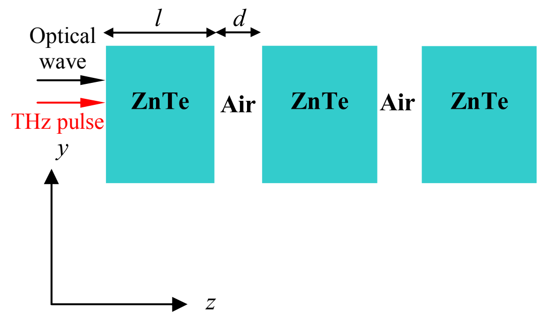

Figure 1. Layered structure of the proposed terahertz detector

V. Conclusion

In this paper, using a layered structure of ZnTe slabs with air gaps, a new method for detection of terahertz pulses with high sensitivity is introduced and its performance is analyzed using the numerical method of FDTD in its nonlinear form. The presence of the terahertz pulses changes the refractive index of the ZnTe slabs and thus shifts the stop-bands of the periodic structure used in the proposed detector. This affects the optical wave intensity. One of the advantages of the proposed method is that a terahertz signal may be detected by sensing the intensity variation instead of sensing the wavelength shift commonly used in detectors based on a single ZnTe layer. This characteristic reduces the detector complexity.

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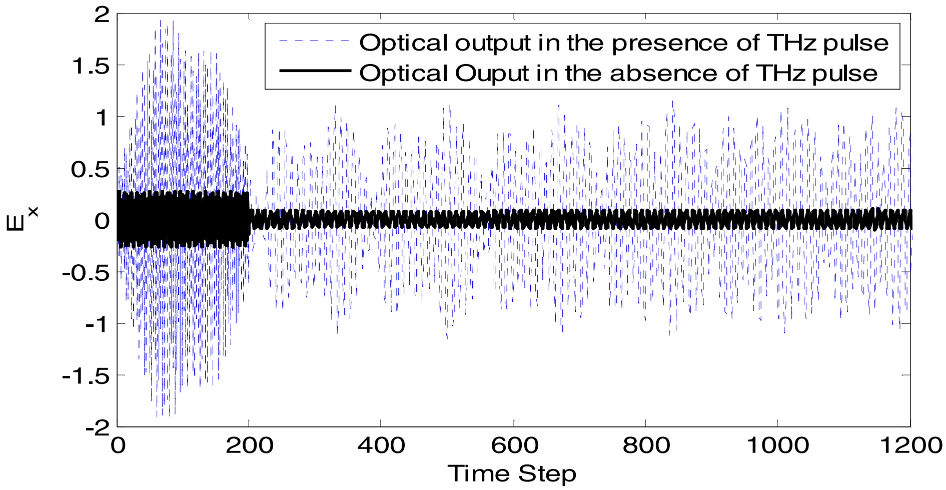
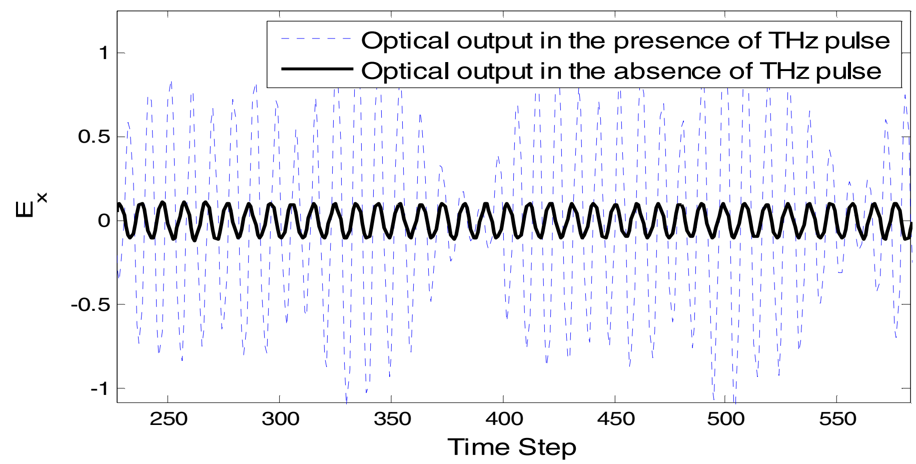


(a)



(b)

Figure 2. (a) Impact of the terahertz pulse on the optical wave (b) A time window of figure (a) to show the details. Note that each time step is $0.083\,p\sec$.

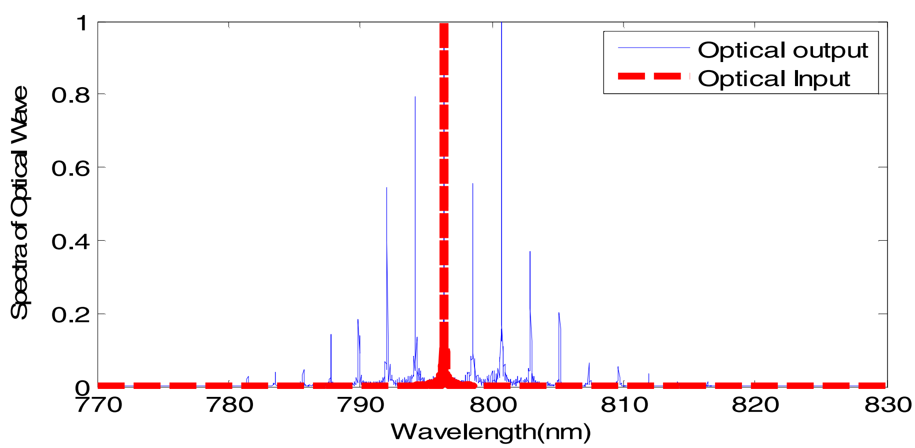


Figure 3. Normalized spectrum of the input and output optical wave in the presence of the terahertz pulse. Generated frequency components are observable in the output spectrum.