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Research Article

Enhanced Reflected Group Delay with Optical Tamm State via Graphene-Dielectric Bragg Mirror Configuration

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Group delay of the optical pulse reflected from the structure composed of graphene and one dimensional photonic crystal (1D PC) is studied. It is shown that the large negative group delay in this configuration can be realized due to the excitation of the optical Tamm state (OTS) at a graphene-dielectric interface. The reflected group delay can be enlarged negatively and can be switched from positive to negative or vice versa. We show that the conductivity of graphene has a significant influence on reflected group delay, making the graphene-PC structure be a good candidate for dynamic tunable optical delay device in the THz frequencies. Furthermore, the influences of the relaxation time of graphene, the incident angel, and the dispersion characteristics of top layer on group delay are clarified.

1. Introduction

The group delay of propagation of electromagnetic wave traversing through a media together with delay control techniques has attracted much attention since it offers many potential applications for optical communication [1, 2]. These techniques can be applied to many optical devices such as all-optical buffers, optical data storage, optical memories, and so on [3–5]. It is common knowledge that "subluminal effect" and "superluminal effect", which exist in high-dispersion device and media, have been investigated both theoretically and experimentally in a variety of structures [6–8]. More recently, Ouchani *et al.* have researched possibility of superluminal and negative delay times for electromagnetic wave propagation in a linear and passive periodic structure consisting of alternating isotropic and anisotropic media [9]. Wang *et al.* showed a tunable transition between positive and negative group delays of light reflection from layer structures with a graphene layer [10]. Li *et al.* fabricated a 24-GHz source-degenerated tunable delay shifter with negative group delay compensation [11]. However, the effective methods of enhancing the group delay of optical pulse are to be improved.

Recently, graphene, an allotrope of carbon and an interesting two-dimensional nanomaterial, has emerged as an important and potential material owing to its outstanding properties received wide attention in various fields such as optoelectronics, materials science, and detection [12–15]. Graphene has many excellent properties in optoelectronics, such as broadband [16], the strong interaction between light and graphene [17], good optical transparency [18], and high electron mobility [19]; especially, graphene conductivity can be flexibly controlled by the external voltage [14, 20]. Therefore, the group delay can be flexibly manipulated by tuning external voltage. For this reason, Bragg cavities consist of graphene and optical lattice seems to be a potential structure for achieving and controlling tunable group delay.

OTS is a surface wave that is confined on the interface of two different media. It has grabbed the attention of researchers due to its strong locality to light and being easily excited [21–25]. In this paper, we proposed a novel structure consists of graphene and optical lattice; it can realize the enhancement of reflected group delay and switch between positive reflected group delay and negative reflected group delay of optical pulse. We theoretically demonstrated that

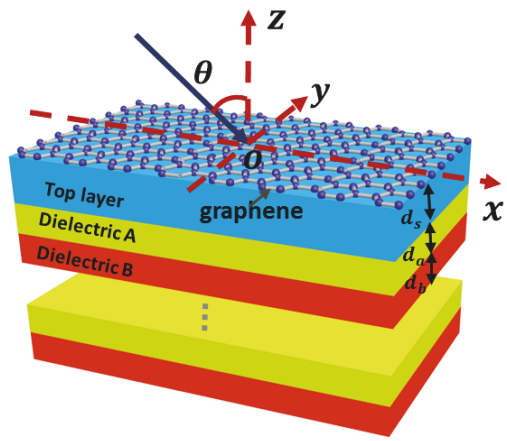

FIGURE 1: Schematic diagram of a graphene-1D PC composite structure. The incident angel is θ. The period of photonic crystal is m = 20.

reflected group delay of optical pulse can be obtained by exciting OTS through graphene. Moreover, group delay can be manipulated by adjusting Fermi energy, incident angle and relaxation time. The effects of slow light and fast light can be continuously tuned in the THz regime. We believe it has potential and important applications in all-optical communication systems, especially for the design of optical delay device.

2. The Theoretical Model and Method

Compared with semiconductor superlattice, both 1D PC heterostructures and distributed Bragg reflector (DBR) are befitting structures for observing OTS as we know. In this paper, our structure is composed of monolayer graphene, top layer, and 1D PC. The monolayer graphene, with a thickness of 0.34 nm, is placed on the top layer. 1D PC which consists of m = 20 cycles is placed on the bottom of the configuration. Nowadays, the fabrication of 1D photonic crystal and the transfer of graphene are mature technologies. It is not hard to fabricate the proposed structure as shown in Figure 1. Hence, this program is feasible [26, 27]. Substrate A with a thickness of d_a and substrate B with a thickness of d_b compose the DBR. The top layer, whose thickness is d_s, is placed between the graphene sheet and 1D PC as shown in Figure 1. Here, poly (4-methyl-1-pentene) (TPX) and SiO_2 are selected for the dielectric materials of substrate A and substrate B in the configuration, whose refractive indices are $n_a = 1.46$ and $n_b = 1.9$ in THz range, respectively. We take no account of the influence of the dielectric loss and under random phase approximation; the surface conductivity of monolayer graphene can be regarded as the sum of σ_{intra} and σ_{inter} [28]. However, in the THz range, the conductivity of graphene can be approximately described as [29]

$$\sigma = \frac{ie^2 E_F}{\pi\hbar^2 (\omega + i/\tau)}, \tag{1}$$

where e is the electron charge; $\hbar$, E_F, τ represent reduced Planck's constant, Fermi energy, and electron-phonon relaxation time, respectively. ω is the angular frequency of incident electromagnetic wave. Here, the thickness of substrate A and substrate B in the composite structure is set as $(1/4n_a)\lambda_c$ and $(1/4n_b)\lambda_c$, respectively. Meanwhile, central wavelength is set as $\lambda_c = 300\ \mu$m. In order to simplify the calculation, we assume that the thickness and refractive index of top layer are as the same as the substrate B. Besides, we choose temperature T = 300 K and relaxation time $\tau = 0.5$ ps. From the equation of conductivity of graphene, we can find that Fermi energy influences the conductivity of graphene; meanwhile Fermi energy can be tuned by external voltage; it means that we can flexibly tune the conductivity of graphene by tuning the external voltage and even tune the optical properties of the composite structure.

For the sake of calculation of the reflected group delay properties of the composite structure, we need to calculate the transmittance and reflectance of the composite structure. In order to obtain the excitation condition associated with OTS, we use the modified transfer matrix method to calculate the transmittance and reflectance of the composite structure [30]. Here, we can ignore the thickness of graphene in the computation. Different from the traditional transfer matrix, the transmission matrix for the TM-polarized at the interface of the composite structure in the paper can be expressed as

$$D_{as} = \frac{1}{2}\begin{bmatrix} 1 + \eta_{TM} + \xi_{TM} & 1 - \eta_{TM} - \xi_{TM} \\ 1 - \eta_{TM} + \xi_{TM} & 1 + \eta_{TM} - \xi_{TM} \end{bmatrix}, \tag{2}$$

where $\eta_{TM} = \varepsilon_a k_{sz}/\varepsilon_s k_{az}$, $\xi_{TM} = \sigma k_{sz}/\varepsilon_0 \varepsilon_s$, $k_{az} = \omega \cos\theta/c$, $k_{sz} = k_0\sqrt{\varepsilon_s - \varepsilon_a \sin^2\theta}$, and θ and ε_0 represent the incident angle of incident electromagnetic wave and the vacuum dielectric constant, respectively. ε_a and ε_s are the dielectric constant of air and top layer, respectively. The transmission matrix for the TE-polarized can also be obtained similarly. Based on the propagation matrix and transfer matrix, we can successfully calculate the transmittance and reflectance of the composite structure. Under the limitation of narrow spectral pulse, the reflected group delay of the composite structure can be written as follows [7]:

$$\tau_r = \left[\frac{\partial \phi_r}{\partial \omega}\right]_{\omega=\omega_c}, \tag{3}$$

where ω_c represents carrier frequency and ϕ_r represents the phase of reflection.

3. Results and Discussions

In the section, we will discuss the characteristics of reflected group delay in the air-graphene-top layer 1D PC composite structure. It is well known that OTS can be directly excited in both the TE- and TM-polarized and occurs even at normal incidence. For the sake of simplicity, we only discuss the TM-polarized for OTS in this paper. In the composite structure, the excitation of OTS creates conditions for the large reflected group delay. Based on the formula (3), the gradient of large

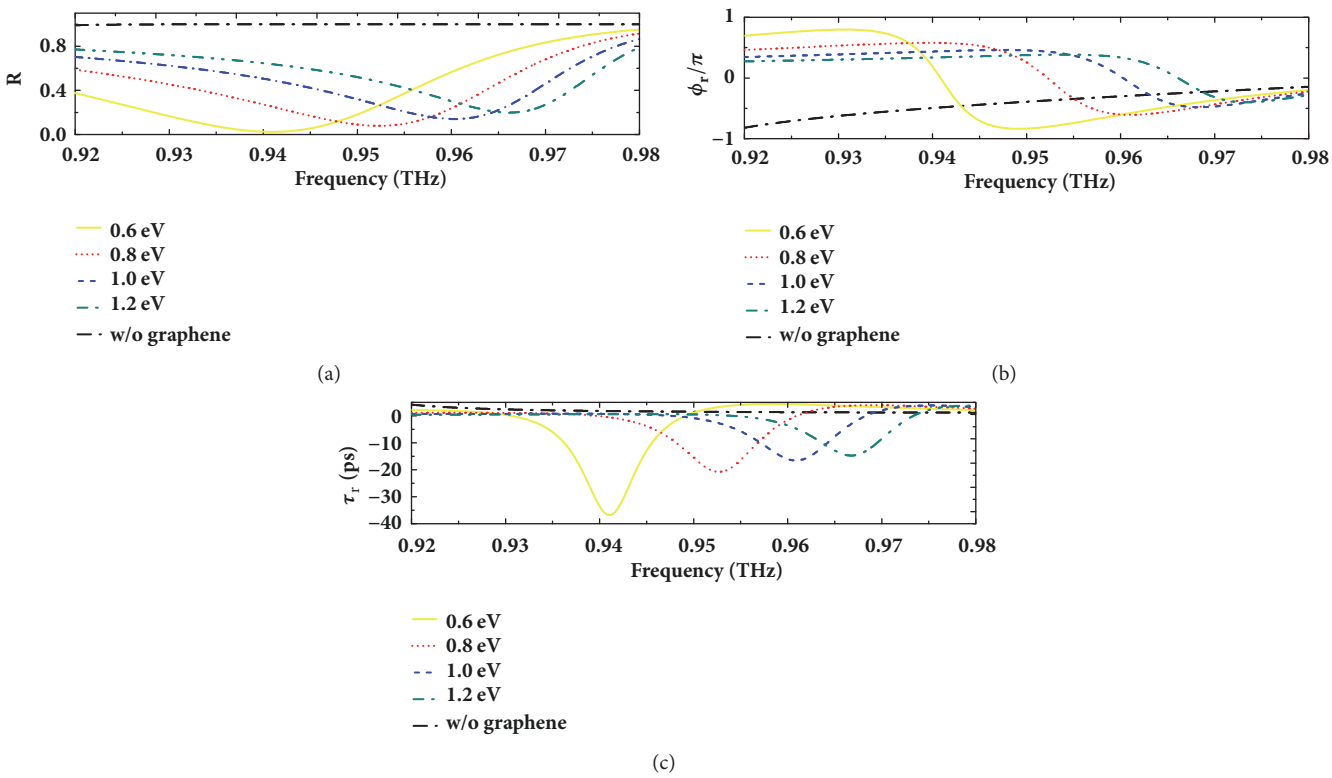

FIGURE 2: (a) Reflectance R, (b) reflected phase ϕ_r, and (c) reflected group delay τ_r as functions of frequency for different Fermi energies in the graphene-1D PC structure. For comparison, reflectance R, reflected phase ϕ_r, and reflected group delay τ_r without graphene is shown as well. Other parameters are the same as before.

positive or negative corresponds to a large reflection group delay in the relationship of reflected phase varying with the frequency, in order to verify the characteristic of group delay of the structure; we plotted the relation of reflectance to reflected phase change with frequency, as shown in Figures 2(a) and 2(b). For simplicity, we assume the electromagnetic wave incident vertically. From Figure 2(a), we can easily see an obvious dip of reflectance at the resonance frequency owing to the excitation of OTS [31]; the dip is caused by the interaction of the real and imaginary parts of the reflection coefficient. Therefore, near the frequency that excites OTS, the reflected phase shows a remarkable monotone decrease and the strongly monotone decrease reflected phase corresponds to a large negative reflected group delay, as shown in Figure 2(b). We have also calculated the reflected group delay of the whole configuration according to formula (3), as shown in Figure 2(c). We can see that the reflected group delay reached about −40 ps at 0.942 THz when Fermi energy is 0.6 eV. A small change of conductivity of graphene can remarkably realize the change of value of reflected group delay; at the moment, the Fermi energy has a great influence on conductivity of graphene, and when the Fermi energy is increase, the negative value of the reflected group delay will decrease, as shown in Figure 2(c). Therefore, we can flexibly manipulate the reflected group delay by tuning the external voltage. It also provides an effective method to manipulate the reflected group delay through external control in fixed structure.

According to (1), it can be seen that the relaxation time of graphene also have a significant influence on the conductivity of graphene. However, the reflectance is strongly dependent on the optical conductivity of graphene owing to the transfer matrix, and the reflected phase and reflected group delay are influenced by the conductivity of graphene. Hence, the reflected group delay and the relaxation time of graphene are highly correlated. In addition, it gives us a new idea to manipulate the reflected group delay through these characteristics. Figure 3 presents the reflected group delay and reflected phase varying with the frequency and the relaxation time. Compared with the impacts of Fermi energy on reflected phase and reflected group delay, the changes of relaxation time of graphene cause the fact that the reflected phase has monotonically increased and monotonically decreased. Therefore, it has positive reflected group delay and negative reflected group delay. As shown in Figure 3(a), when relaxation time is below 1 ps, the reflected phase becomes steeper with the increase of relaxation time near resonance frequency, and the negative reflected group time of the composite structure approximates the maximum near the resonance point. Particularly, when relaxation time is above 1 ps, the curve of reflected phase is monotonically increasing; it means that the negative reflected group delay can be converted to the positive reflected group delay under certain conditions. In the paper, the value of reflected group delay can be reached about −90 ps and 80 ps. The variation of relaxation time is hardly affecting the reflected group delay

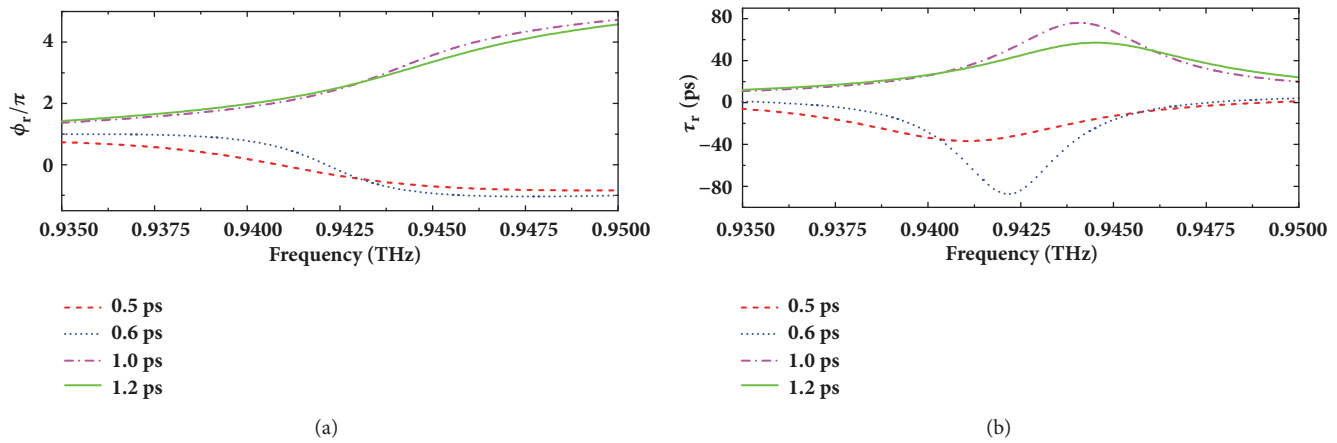

FIGURE 3: (a) Reflected phase ϕ_r and (b) reflected group delay τ_r as functions of frequency for different relaxation time in the graphene-1D-PC structure. Other parameters are the same as before.

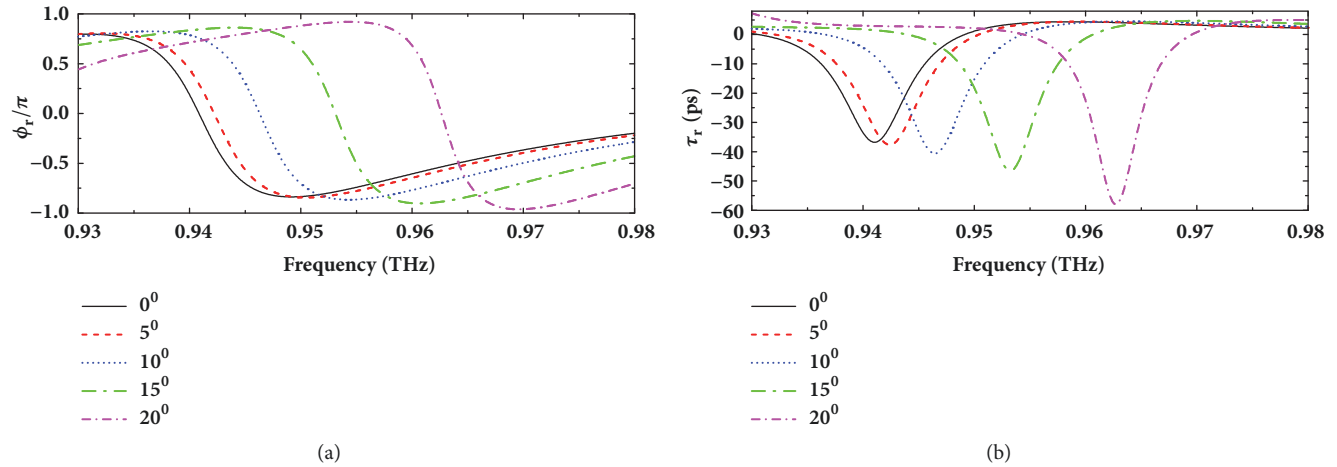

FIGURE 4: (a) Reflected phase ϕ_r and (b) reflected group delay τ_r as functions of frequency for different incident angel in the graphene-1D-PC structure. Other parameters are the same as before.

in fixed configuration. Notwithstanding, it also provides a feasible method to convert the reflected group delay time symbols.

Although OTS can be excited by normal incidence, the excited condition of OTS has differences in different incident angle; it also provides an idea for manipulating the reflected group delay. We have also discussed the influence of incident angel on reflected group delay in the graphene-1D PC composite structure as well. The change rules of the reflected phase and the reflected group delay under different incident angle are shown in Figure 4. With the incidence of angel gradual increase from zero degrees, the curve of the reflected phase becomes steeper; thus the value of the reflected group delay of the composite structure becomes larger. We can see that the reflected group delay reached about −60 ps when the incidence of angel is 20 degree.

Next, we discuss the impact of dispersion characteristics of top layer on the reflected group delay. In our composite structure, embed the top layer to observe the change of reflected group delay. The top layer can modulate the OTS, and we can infer that varying the parameters of the top layer will change the eigenfrequency of the OTS based on the composite structure. Figure 5 shows the variation of the reflected group delay with the thickness of the top layer and dielectric constant of the top layer in TM polarization. From Figure 5(a), as the thickness of top layer increases, we can see that negative value of reflected group delay will increase remarkably as well. Negative value of reflected group delay can reach about −60 ps, and the negative reflected group delay becomes relatively stable over 45 μm. Besides, we also discussed the influence of dielectric constant of top layer, according to the formula; we can control the dielectric constant of top layer just by adjusting the refractive index of top layer. As shown in Figure 5(b), when the dielectric constant of top layer increases, the negative value of reflected group delay also increases and becomes stable. Compared with the influence of thickness of top layer, the reflected group delay is more sensitive to the dielectric constant of top layer. Therefore, we can tune the thickness and dielectric constant of top layer to control the reflected group delay better.

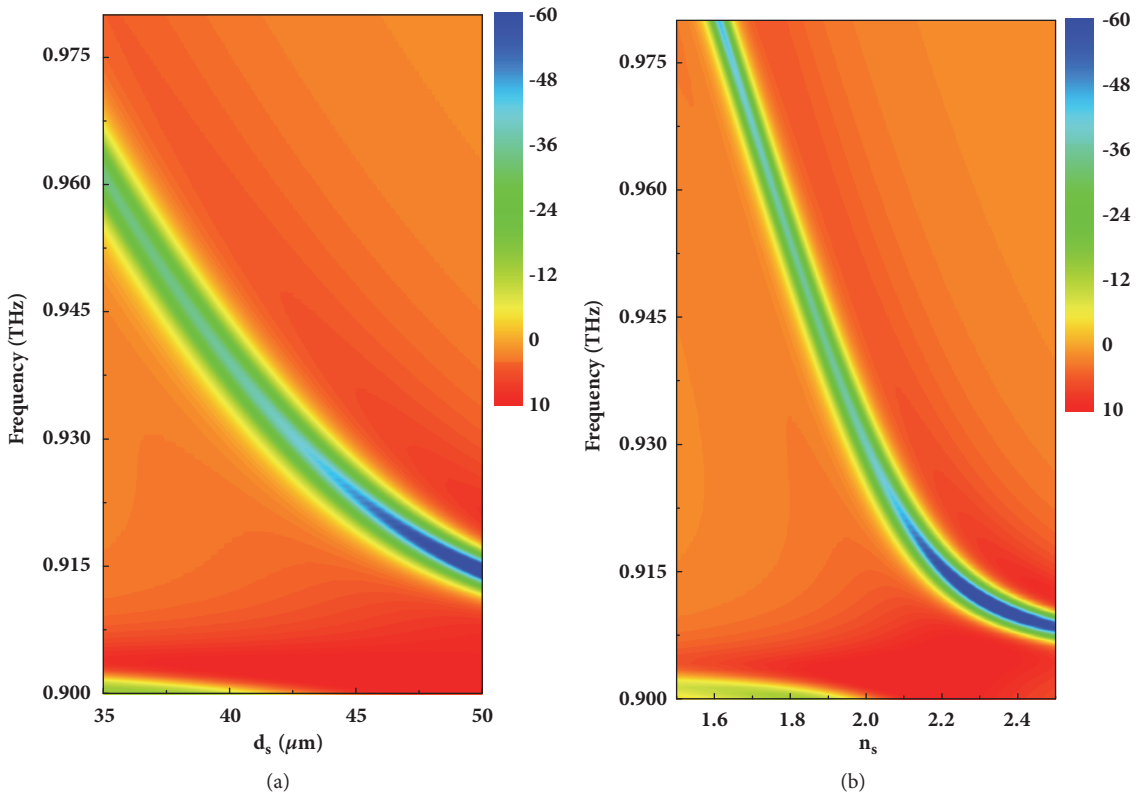

FIGURE 5: (a) Reflected group delay τ_r as a function of frequency and d_s for the graphene-1DPC structure. (b) Reflected group delay τ_r as a function of frequency and ε_s for the graphene-1DPC structure. Other parameters are the same as before.

4. Conclusions

In conclusion, we proposed a method to enhance the reflected group delay via excite OTS in a graphene-1D PC composite configuration. It is found that the value of the reflected group delay has a remarkable increase in the composite structure, the negative reflected group delay can be reached about −80 ps under the appropriate parameters, and we can realize a transition between negative and positive reflected group delay through tuning the relaxation time. Moreover, the simulation results reveal that Fermi energy, the incident angel, and the dispersion characteristics of top layer will influence the reflected group delay as well. It means that the reflected group delay extremely depends on the properties of graphene; therefore, it provides an effective and feasible way to enhance and control the reflected group delay. We believe that tunable negative and positive reflected group delay via exciting OTS in a graphene-1D PC composite configuration will be better applied to optical delay device and other optical fields.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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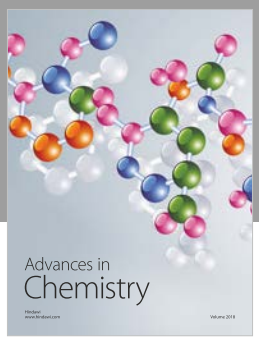

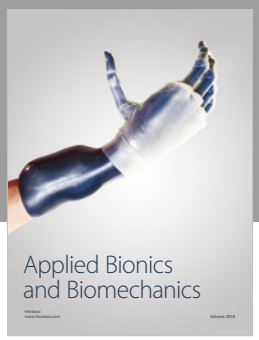

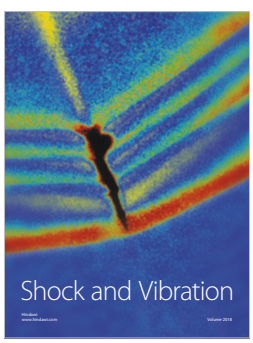

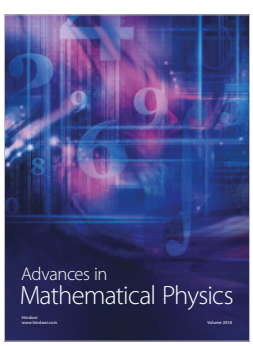

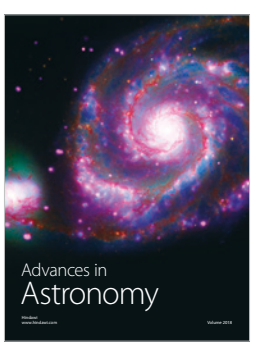

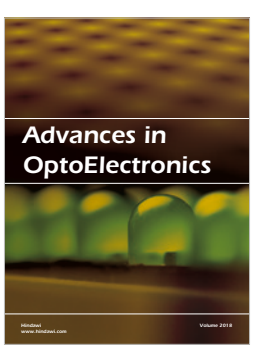

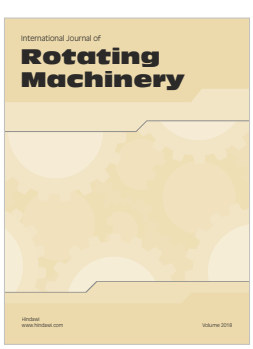

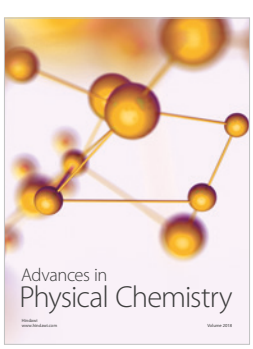

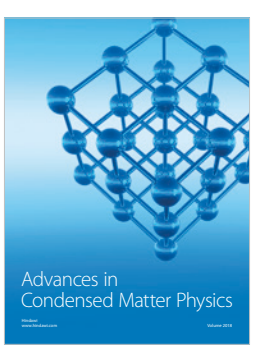

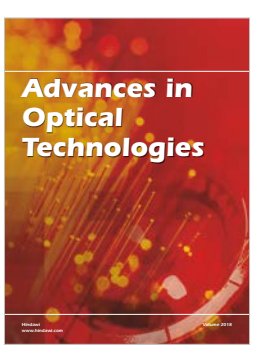

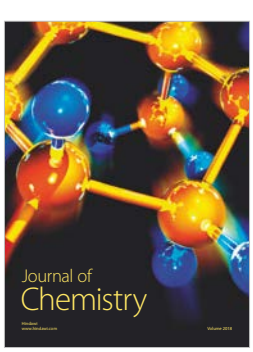

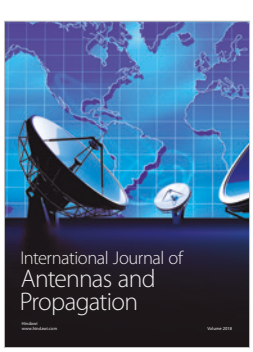

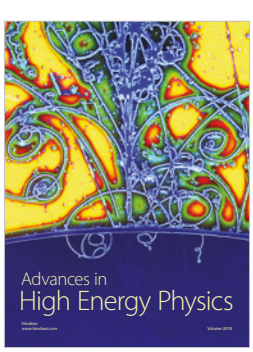

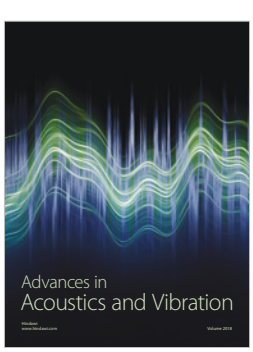

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