Ultrafast all-optical switching in the presence of Bloch surface waves

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Abstract. It is commonly known that Bloch surface waves (BSW) can be excited at the photonic crystal/dielectric boundary that leads to many features attractive for application these states as the basis of sensors and nanophotonic devices. The narrow spectral-angular resonance of BSW is very sensitive to properties of top layer and surrounding medium. There are few ways to enhance nonlinear optical response of a top layer without violation of BSW excitation conditions. In this work we choose graphene monolayer as a source of strong nonlinearity with tiny thickness. We study temporal nonlinear optical response of graphene in the case of Bloch surface waves excitation revealing subpicosecond switching time of probe dynamics.

1. Introduction

Bloch surface waves (BSW) are propagating electromagnetic states which can be exited at the surface of one-dimensional (1D) photonic crystals (PC) within its photonic band gap. As an alternative to surface plasmon-polaritons (SPP), BSW show dramatically enhanced propagation lengths up to several millimeters range [1] and provide new optical opportunities such as the possibility to obtain TE or TM-polarized surface waves. BSW manifest themselves as narrow spectral-angular resonances in reflectance spectra. The resonance position strongly depends on the parameters of the top layer of PC [2] and surrounding medium. In order to enhance nonlinear properties of top layer it is possible to use thin film of nonlinear substances placing to the surface of the PC. For example graphene monolayer has high third-linear order susceptibility [3], but due to the small thickness does not significantly change the BSW excitation conditions [4].

Recently, the BSW were proposed as a basis for the new planar photonic devices able to control light propagation. The possibility of using the BSW as waveguides [5], sensors [6] and elements of integrated circuits [7] had been recently studied. But the possibility of using the BSW as the basis of optical modulators hasn’t been studied so far. In this work we use pump-probe technique in the Kretschmann prism configuration to study temporal dynamics of optical response of graphene monolayer placing at the surface of 1D PC in the case of Bloch surface waves excitation. The probe dynamics revealed subpicosecond switching time with oscillation modulation behavior of the reflection coefficient.

2. Results and discussion

2.1 Sample design

The sample was 1D PC which consists of 7 pairs of alternating quarter wavelength-thick SiO2/Ta2O5 layers deposited on quartz substrate by thermal vacuum deposition. The thicknesses of SiO2/Ta2O5
layers were calculated by transfer matrix method [8] for exciting the BSW in the Kretschmann configuration within the operating range of a Ti:Sapphire laser (750-850 nm) at 45-degree incident angle and corresponded to 112 nm and 160 nm respectively. To demonstrate the dependence of the switching modulation on the nonlinear susceptibility of top PC layer, we used the sample with graphene layer placed to the PC surface. Graphene monolayer was prepared by chemical vapor deposition on the nickel foil and transferred to the PC surface [9].

2.2 Experimental setup
The scheme of experimental setup is presented in Fig.1. The pump-probe setup was based on Coherent Micra Ti:Sapphire laser with pulse precompressor which provided a train of femtosecond pulses with duration of 50 fs at the sample area and repetition rate of 80 MHz. The laser radiation was split into pump and probe beams in the ratio 8:1. The sample was attached to the right angle prism using immersion oil. The prism was installed on the motorized stage allowing to change the angle of incidence with 0.01 degree accuracy. The p-polarized pump beam was passed through a delay line and focused on the PC under the normal incidence at the opposite side of prism. The s-polarized probe beam was focused on the sample through the prism at nearly 45 degree of incident angle to excite the BSW. To observe the narrow spectral-angular resonance of BSW a spatial filtration scheme consisting of lens, aperture and monochromator was used. The aperture was placed at lens back focal plane where the different points of focused beam correspond to different propagation angles of reflected probe radiation. This system allowed to perform spectroscopic measurement of signal for a small set of angles determined by aperture diameter. The delay line was consisted of a motorized stage with 0.5 um step, corresponding to a temporal resolution of 3 fs. To reduce signal/noise ratio the synchronous detection technique based on photoelastic modulator (PEM) was used. The half-wavelength plate (λ/2) and Glan-Taylor prisms (GT) allowed to control power and polarization of radiation. The fluence of pump beam could be set up to 400 uJ*cm⁻².

![Figure 1. Scheme of experimental setup.](image)

2.3 BSW excitation detection
The excitation of the BSW was determined by a sharp dip in spectrum of probe pulses reflected from the sample. Besides, the BSW was directly visualized on the surface of the PC by CMOS-camera. Unpumped spectra of probe pulses reflected from PC without graphene monolayer are presented in Fig.2. BSW is excited for s-polarized probe radiation. It can be detected by the emergence of resonance in the reflection spectrum. BSW is clearly visible by the camera image (Fig.2 (b)). In the case of p-polarized probe BSW excitation doesn’t occur.
2.4 Pump-probe experiment

For investigation of nonlinear optical response of graphene monolayer the pump fluence was chosen about 50 μJ/cm² that is lower than fluence corresponds to graphene threshold damage [10]. Fig.3 (b) presents the normalized unpumped reflectance spectrum of PC with graphene monolayer. The BSW resonance is observed near the central wavelength of 785 nm. It can be seen that the placing of graphene at the photonic crystal leads to widening of BSW resonance and decreasing of Q-factor.

Fig.3 (a) shows relative change dR/R in reflectance of the sample. Signal was measured by integrating over the all pulse wavelengths (760 - 810 nm). The case of the temporal dynamics of graphene placed on the dielectric substrate has been recently studied enough [11]. Here we observe the oscillation behavior of reflectance, which completely relaxes to the unperturbed value after 3 ps. This behaviour is the result of superposition of shift and Q-factor decreasing of the BSW resonance [12] and graphene relaxation dynamics. The full width at half-maximum of the positive modulation spike is about 110 fs. The switching time from positive to negative reflectance modulation is 150 fs. This behaviour makes it possible to use the investigation system as a light modulator.

![Figure 2](image2.png)

**Figure 2.** (a) Unpumped spectrum of s-(red line) and p-polarized (black line) probe pulse reflected from the sample. (b) CMOS-camera images.

![Figure 3](image3.png)

**Figure 3.** (a) Transient relative change of the sample reflectance measured over all pulse wavelengths. Shaded area shows the pump-probe cross-correlation. (b) Normalized reflectance spectrum of sample with graphene monolayer.
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