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All-optical loss modulation with graphene-buried polymer waveguides

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We present an analysis of all-optical loss modulation in a graphene-buried waveguide based on the Pauli blocking effect. We show that, to realize effective loss modulation, both the signal light and the co-propagating control light must be polarized along the direction in parallel with graphene's surface and the loss-modulation efficiency is given by the ratio of the loss coefficients of the signal light and the control light. To demonstrate the principle, we fabricate two polymer waveguide samples, one with a 0.6-mm long graphene film buried in the center of the waveguide core and the other with a 10.0-mm long graphene film placed on the top surface of the core. We achieve a loss modulation to 1550-nm signal light from 5.0 to 0.4 dB with a 980-nm control power varying from 6.5 to 12. 5 dBm for the first sample, and from 8.0 to 0.5 dB with a control power varying from 14.5 to 19.5 dBm for the second sample. The experimental results agree well with the theoretical analysis. A graphene-buried waveguide offers much flexibility as a platform for the realization of all-optical devices, such as optical switches, optical samplers, and optically tunable attenuators.

OCIS codes: (130.3120) Integrated optics devices; (130.5460) Polymer waveguides; (130.4815) Optical switching devices; (310.3915) Metallic, opaque, and absorbing coatings.

All-optical control, which refers to direct control of light with light, is a subject of scientific and application interest. Many nonlinear systems have been demonstrated for all-optical control, which include, for example, photonic-crystal cavities [1], silicon resonant structures [2], and doped-glass fibers [3]. Although the performance of all-optical control devices in terms of switching/modulation speed and efficiency has improved significantly over the years, narrow-band operation, design complexity, and expensive technology are among the key issues that still need to be addressed. The advances in the study of graphene in recent years have opened up new opportunities in nonlinear optics. Being a single layer of carbon atoms arranged in a hexagonal structure, graphene possesses many excellent optical properties. Its strong optical nonlinearity has found applications in optical polarizers [4,5], fiber lasers [6,7], optical modulators [5,8–10], etc. The present study considers all-optical modulation with graphene.

When graphene is excited with both short-wavelength and long-wavelength light, the absorption of short-wavelength light can block the absorption of long-wavelength light [11]. This phenomenon is a manifestation of the Pauli blocking effect, where the electron-hole pairs generated by graphene's absorption of high-energy photons fill up the low-level energy bands of graphene and thus block the absorption of low-energy photons [11]. This mechanism has been explored for achieving broadband all-optical switching or modulation with microfibers [11–13]. By using a 1.4-μm-diameter microfiber coated with a bi-layer 16-μm long graphene, all-optical switching at 1550 nm with an extinction ratio of 38% and a response time of 2.2 ps has been achieved with 1064-nm control pulses that have a peak power of 400 W [11]. By using a 3-μm-diameter microfiber wrapped around a graphene-coated rod of 12-mm long, a broadband all-optical modulator operating from 1525 to 1565 nm with a modulation depth of 7.5 dB at a 980-nm CW control power of 35 mW has been realized [12]. By using an 8-μm diameter microfiber coated with a 5-mm long graphene bilayer, all-optical modulation from 1520 to 1570 nm with a modulation depth of 13 dB has been achieved at a 1060-nm CW control power of 2.2 W [13].

The main reason of using a microfiber in the demonstration of all-optical control [11–13] is to increase the optical field around the fiber, so that light propagating in the fiber can interact strongly with a graphene film coated or attached onto the fiber. Because a microfiber has a circular geometry and a large refractive index compared with air, it is impossible to control the polarization state of light to achieve the strongest possible light-graphene interaction. As graphene can only be attached onto the surface of a microfiber, the design flexibility is limited. The difficulty in the control of the diameter and the length of a microfiber results in poor repeatability in device fabrication. There are also practical issues in the handling and the packaging of microfiber devices.

In this letter, we present a study of all-optical modulation based on the Pauli blocking effect with graphene-buried polymer waveguides. Unlike high-index-contrast waveguides, which support hybrid modes, small-index-contrast polymer waveguides support almost pure linearly polarized modes. Our recent findings [14] show that graphene strongly absorbs the transverse-electric (TE) modes, which are linearly polarized along graphene's surface, while exhibiting little absorption to the transverse-magnetic (TM) modes, which are approximately linearly polarized along the direction perpendicular to graphene's surface. We have applied this property of graphene to the realization of ultra-broadband mode filters [15], lithium-niobate electro-optic devices [16], and polymer thermo-optic switches [17]. When applying the Pauli blocking effect to a graphene-buried polymer waveguide, we expect the effect be maximized by propagating both the signal light and the control light along the waveguide as the TE modes. There is also much flexibility in the control of the characteristics of the all-optical device by controlling the dimensions of the graphene film and its location in the waveguide. The spin-coating process available with polymer material allows easy formation of multilayer polymer films and hence the insertion of one or more graphene films in a waveguide [15]. In addition, polymer waveguides are compatible with fibers in size and refractive index, which can facilitate device packaging. The polymer waveguide technology is potentially a low-cost technology for mass production of all-optical control devices. Many of these advantages are not available with high-index waveguide systems, such as graphene-buried chalcogenide glass waveguides [5] and graphene-covered silicon waveguides [8–10].

Here we first present a simple theoretical analysis of the all-optical loss modulation effect in a graphene-buried polymer waveguide and then experimental results of two waveguide samples to demonstrate the flexibility of the technology. For one sample, which contains a 0.6-mm long graphene film buried in the center of the waveguide core, by varying 980-nm control power from 6.5 to 12.5 dBm, the graphene-induced loss to 1550-nm signal light is reduced from 5.0 to 0.4 dB, which gives a loss modulation of 4.6 dB. For the other sample, which contains a 10-mm long graphene film placed on the top of the core, by varying 980-nm control power from 14.5 to 19.5 dBm, the graphene-induced loss to 1550-nm signal light is reduced from 8.0 to 0.5 dB, which gives a loss modulation of 7.5 dB.

We consider a waveguide that contains a graphene film with length L. We assume that the waveguide material is lossless and both the signal light and the control light propagating along the waveguide are TE-polarized. In the absence of the control light, the graphene-induced loss to the signal light is $\alpha_{\mathrm{signal}}L$, where α_{signal} is the loss coefficient of the signal light (in dB/unit length). In the presence of the control light, a length of the graphene film no longer absorbs the signal light. This length, referred to as the loss-blocking length L_{blocking}, is a function of the control power launched into the waveguide, denoted as W_{control}. The graphene-induced loss to the signal light, denoted as $Loss(W_{\mathrm{control}})$ (in dB), is then given by

$$Loss(W_{\mathrm{control}}) = \alpha_{\mathrm{signal}}[L - L_{\mathrm{blocking}}(W_{\mathrm{control}})] \qquad \textbf{(1)}$$

with $L \geq L_{\mathrm{blocking}}$. For the Pauli blocking effect to take effect, the control power must be larger than a threshold value, denoted as W_{th}. According to the definition of the loss-blocking length, the input control power W_{control} is attenuated by the graphene film to the threshold value W_{th} over the loss-blocking length, i.e.,

$$\alpha_{\mathrm{control}}L_{\mathrm{blocking}}(W_{\mathrm{control}}) = W_{\mathrm{control}} - W_{\mathrm{th}}, \qquad \textbf{(2)}$$

where $\alpha_{\mathrm{control}}$ (in dB/unit length) is the loss coefficient of the control light and both W_{control} and W_{th} are in dBm. As suggested by Eq. (1), the graphene-induced loss to the signal light can be completely suppressed by choosing a graphene length equal to the loss-blocking length, which, according to Eq. (2), depends on the control power. A larger control power gives a longer loss-blocking length and thus allows a longer graphene length to be used for achieving a wider loss-modulation range. After eliminating L_{blocking} from Eq. (1) with Eq. (2), we find

$$Loss(W_{\mathrm{control}}) = -\frac{\alpha_{\mathrm{signal}}}{\alpha_{\mathrm{control}}}(W_{\mathrm{control}} - W_{\mathrm{th}}) + \alpha_{\mathrm{signal}}L, \qquad \textbf{(3)}$$

which shows that the graphene-induced loss to the signal light decreases linearly with the control power at a rate of $\alpha_{\mathrm{signal}}/\alpha_{\mathrm{control}}$. This rate, referred to as the loss-modulation efficiency, is a measure of the significance of the loss-modulation effect. The optimal length required is L_{blocking},. A longer length gives an extra signal loss without changing the loss-modulation efficiency.

Figure 1(a) shows a schematic diagram of the cross section of the waveguide considered in our study, which consists of a rectangular core with refractive index n_1 surrounded by a cladding with refractive index n_2 and a graphene film buried in the waveguide at a distance d from the center of the core. In our analysis, the wavelengths of the signal light and the control light are fixed at 1550 nm and 980 nm, respectively. We assume $n_1 = 1.572$ and $n_2 = 1.562$, which are the refractive indices of the polymer materials used in the fabrication work. We consider a core with a width of $w = 8$ μm and a thickness of $2t = 10$ μm. Because the index difference between the core and the cladding is small, the modes supported by the waveguide are approximately linearly polarized with dominant electric fields along either the x direction (the TE modes) or the y directions (the TM modes). The power profiles of the TE_{00} modes at 1550 and 980 nm,

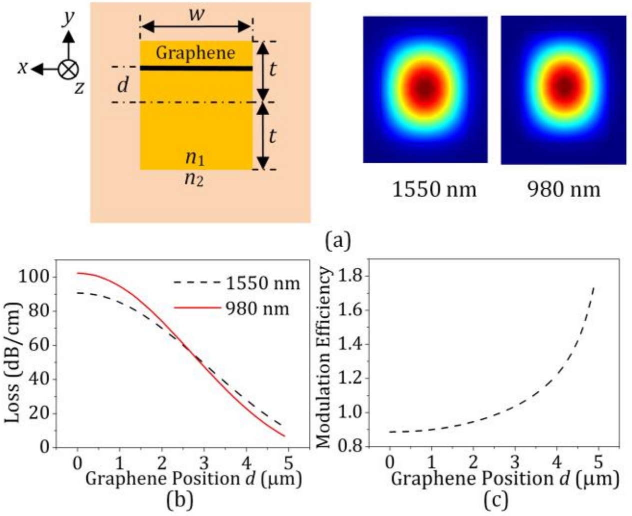


Fig. 1. (a) Schematic diagram of the cross section of a graphene-buried waveguide and the power profiles of the TE_{00} modes at 1550 and 980 nm, (b) variations of the graphene-induced losses at 1550 nm and 980 nm with the graphene position d for the TE_{00} mode, and (c) dependence of the loss-modulation efficiency on the graphene position d.

calculated with the commercial mode solver (COMSOL), are shown in Fig 1(a). We apply the interface model of graphene [14] to calculate the graphene-induced losses to the TE$_{00}$ modes at these two wavelengths. The variations of the graphene-induced losses at 1550 and 980 nm with the graphene position d are shown in Fig. 1(b) and the dependence of the loss-modulation efficiency on d is shown in Fig. 1(c). An increase in the distance d leads to an increase in the loss-modulation efficiency, which is due to the fact that the mode at 980 nm is more confined towards the center of the core than the mode at 1550 nm.

To experimentally demonstrate the loss-modulation effect and verify our theoretical analysis, we fabricated two waveguide samples with polymer materials EpoCore and EpoClad (Micro Resist Technology) as the core and the cladding material, respectively, using the standard microfabrication processes [14,15]. One sample (Sample 1) contains a 0.6-mm-long graphene film placed in the center of the core and the other sample (Sample 2) contains a 10-mm-long graphene film placed on the top of the core. For both samples, the width and the height of the core are ~8 μm and ~10 μm, respectively, and the waveguide length is ~10 mm. The monolayer graphene film used was a commercial product (Hefei Vigon Tech.) that came with a size of 10 x 10 mm^2 as an attachment to a PMMA buffer. The processes of transferring the graphene film onto the waveguide sample and trimming its length are detailed in [15]. We actually fabricated a large number of identical graphene-buried waveguides together with reference waveguides without graphene. Figure 2(a) and (b) show the cross sections of two fabricated graphene-buried waveguides.

To characterize the fabricated waveguides, we used a tunable laser (HP8168F) as the 1550-nm signal light source and a 980-nm laser diode (Max-Ray Photonics) as the control light source. The output power of the 1550-nm light was fixed at ~0.5 mW, while the output power of the 980-nm laser could be controlled by varying the injection current. We launched both the 1550-nm and 980-nm light together into the waveguide sample under test with a fiber-pigtailed 980/1550 wavelength multiplexer and controlled the polarization states of the signal light and the control light independently with separate polarization controllers. We should note that the graphene film was terminated at one end of the waveguide and this end was used as the input end. The output light from the other end was collected with a single-mode fiber and analyzed with an optical spectrum analyzer (OSA). The use of an OSA allowed simultaneous measurements of the output powers at the two wavelengths without using a wavelength demultiplexer. By comparing the output powers from the graphene-buried waveguides and the reference waveguides without graphene, we found that the graphene-induced losses to the TE-polarized light at 1550 and 980 nm were ~5.0 and ~6.0 dB, respectively, for Sample 1, and ~8.0 and ~5.5 dB, respectively, for Sample 2. The corresponding loss coefficients at 1550 and 980 nm are ~83 and ~100 dB/cm, respectively, for Sample 1, and ~8.0 and ~5.5 dB/cm, respectively, for Sample 2, which agree reasonably well with the theoretical values at d = 0 and 5 μm shown in Fig. 1(b). On the other hand, the graphene-induced losses to the TM-polarized light at both wavelengths were negligible, as expected. The variations of the graphene-induced losses to the 1550-nm light with the 980-nm control power measured for different combinations of the polarizations of the 1550-nm and 980-nm light are shown in Fig. 3 and 4 for the two samples, respectively. The control power shown in Fig. 3 and Fig. 4 is the output power from the launching fiber, so the actual control power experienced by the graphene film should be slightly lower. For both samples, when either the 980-nm light or the 1550-nm light is TM-polarized, there is no loss modulation to the 1550-nm light. Only when both the 980-nm light and the 1550-nm light are TE-polarized, there is significant loss modulation to the 1550-nm light.

As shown in Fig. 3(d) and Fig. 4(d), the graphene-induced loss to the 1550-nm light decreases linearly with the input control power with a slope of ~0.85 for Sample 1 and ~1.5 for Sample 2, which agree closely with the corresponding measured loss ratios $\alpha_{\text{signal}}/\alpha_{\text{control}} \sim$ 0.83 and 1.45. These measured values also agree well with the theoretical values 0.88 and 1.74 shown in Fig. 1(c). The experimental results confirm the theoretical finding that the loss-modulation efficiency is equal to the ratio of the loss coefficients of the signal light and the control light. For Sample 1, the graphene-induced loss is reduced from 5.0 to 0.4 dB (which gives a modulation depth of 4.6 dB) with a control power varying from 6.5 to 12.5 dBm. For Sample 2, the graphene-induced loss is

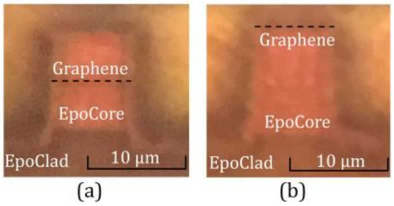


Fig. 2. Cross sections of two fabricated graphene-buried waveguides: (a) one with graphene placed in the center of the core (Sample 1) and (b) the other with graphene placed on the top of the core (Sample 2).

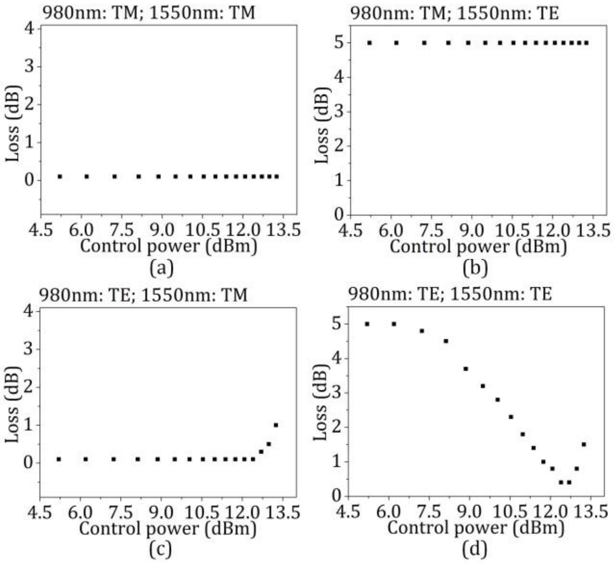
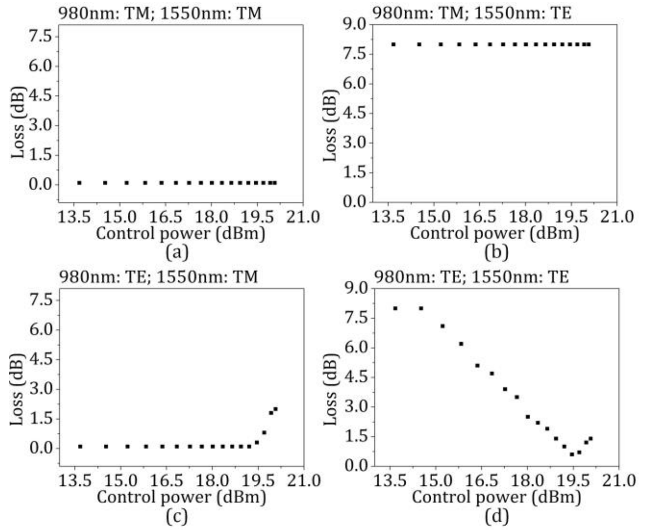


Fig. 3. Variation of the measured graphene-induced loss to the 1550-nm light with the 980-nm control power for the sample with graphene buried in the center (Sample 1): (a) TM-polarized 980-nm control light and 1550-nm signal light; (b) TM-polarized 980-nm control light and TE-polarized 1550-nm signal light; (c) TE-polarized 980-nm light and TM-polarized 1550-nm signal light; and (d) TE-polarized 980-nm control light and 1550-nm signal light.

reduced from 8.0 to 0.5 dB (which gives a modulation depth of 7.5 dB) with a control power varying from 14.5 to 19.5 dBm. In bothcases, almost all the graphene-absorption loss to the signal light is suppressed by the absorption of the control light, as suggested by Eq. (1). The increase of the loss for the 1550-nm light at a control power larger than 12.5 dBm for Sample 1 or 19.5 dBm for Sample 2 could be caused by waveguide deformation or damage due to excessive heating from the absorption of the control light [12]. For Sample 1, with α_{control} = 100 dB/cm, L_{blocking} = 0.6 mm, and W_{control} = 12.5 dBm, we find W_{th} = 6.5 dBm from Eq. (2). Similarly, for Sample 2, with α_{control} = 5.5 dB/cm, L_{blocking} = 10 mm, and W_{control} = 19.5 dBm, we find W_{th} = 14 dBm. These threshold powers agree with the measured values shown in Fig. 3(d) and Fig. 4(d), which thus verifies the validity of Eq. (2). When the graphene film is placed far from the center of the core, the loss-modulation efficiency becomes larger, but the threshold control power also becomes larger. We obtained similar results by varying the signal wavelength over the C-band, which confirms the broadband absorption characteristic of graphene, as already demonstrated by others [12,13]. Our waveguide losses are 1 – 2 dB/cm at 980 and 1550 nm, which are much smaller than the graphene-induced losses shown in Fig. 1(b) for Sample 1 and become relatively significant for Sample 2. Our theory with the waveguide loss ignored is more accurate for Sample 1. The waveguide loss at the control wavelength can increase the threshold control power. The waveguide losses could be reduced by using polymer materials with lower losses [18]. Excitation of higher-order modes by the control light should also contribute to the discrepancies between the measurements and the theory.

In summary, we have demonstrated all-optical control of the modal loss based on the Pauli blocking effect with two graphene-buried polymer waveguide samples using 1550-nm signal light and 980-nm control light. We have made clear the polarization dependence of the Pauli blocking effect, which is important for the application of this effect. To maximize loss modulation, both the signal light and the control light must be TE-polarized, which also suggests the possibility of modulating the signal light by modulating the polarization state of the control light. For the waveguide with graphene buried in the center of the core, by varying the control power from 6.5 to 12.5 dBm (or from 4.5 to 17.8 mW), the graphene-induced loss to the signal light is reduced from 5.0 to 0.4 dB and the loss-modulation efficiency is ~0.85. For the waveguide with graphene placed on the top surface of the core, the graphene-induced loss to the signal light is reduced from 8.0 to 0.5 dB with the control power varying from 14.5 to 19.5 dBm (or from 28 to 89 mW) and the loss-modulation efficiency is ~1.5. The experimental results verify the theoretical finding that the loss-modulation efficiency is equal to the ratio of the loss coefficients of the signal light and the control light. The use of a graphene-buried waveguide allows the loss-modulation efficiency and the threshold control power to be tailored by varying the waveguide design, controlling the dimensions and the position of the graphene film in the waveguide, or using different modes for the signal and the control light, and thus offers much flexibility in the design of new devices for all-optical signal processing.



(a) (b) (c) (d)

Fig. 4. Variation of the measured graphene-induced loss to the 1550-nm light with the 980-nm control power for the sample with graphene placed on the top of the core (Sample 2): (a) TM-polarized 980-nm control light and 1550-nm signal light; (b) TM-polarized 980-nm control light and TE-polarized 1550-nm signal light; (c) TE-polarized 980-nm light and TM-polarized 1550-nm signal light; and (d) TE-polarized 980-nm control light and 1550-nm signal light.

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