Research article

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Strong electro-optic absorption spanning nearly two octaves in an all-fiber graphene device

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Abstract: An efficient electro-optic transition control is reported in all-fiber graphene devices over a broad spectral range from visible to near-infrared. The ion liquid-based gating device fabricated onto a side-polished fiber with high numerical aperture significantly enhances the light-matter interaction with graphene, resulting in strong and nonresonant electro-optic absorption of up to 25.5 dB in the wavelength ranging from 532 to 1950 nm. A comprehensive analysis of the optical and electrical properties of the device fabricated with monolayer and bilayer graphene revealed that the number of graphene layers significantly impacts on the performance of the device, including modulation depth and driving voltage. Wavelength-dependent optical response is also measured, which clearly characterizes the electronic bandgap dispersion of graphene. The device exhibited more efficient electro-optic modulation in the longer wavelength region, where the maximum light modulation efficiency of 286.3%/V is achieved at a wavelength of 1950 nm.

Keywords: electro-optic absorption; fiber optic devices; graphene.

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1 Introduction

Recently, optical and optoelectric devices have been actively studied based on two-dimensional (2D) layered materials, including graphene and transition metal dichalcogenides because of their distinct advantages over traditional bulk materials [1–5]. For example, graphene-based optical devices potentially operate in a very wide spectral range, from visible to THz, due to its gapless linear bandgap characteristics. Two-dimensional materials are also easily integrated into various optical structures such as waveguides, optical fibers, and microresonators. In addition, the optical properties of the 2D material have been found to be efficiently controlled using electrical, optical, and chemical methods.

2D-material-based optical modulators that modulate the intensity, phase, or polarization of the incident light have been extensively developed over the past few years using various mechanisms such as electro-optic, all-optical, and thermo-optic modulation [6–11]. All-fiber optical modulators with 2D materials have attracted particular attention as they are compatible with fiber-optic communications or fiber laser systems. Moreover, since the optical fiber has a very small propagation loss and a relatively small core size, it potentially achieves strong interaction between the 2D materials and propagating light along the optical fiber [12].

All-fiber nonlinear optic switches, known as in-line saturable absorbers, are among the most successful applications of all-fiber optical modulators based on the 2D materials. They have been successfully employed to generate the ultrashort optical pulses through the passive mode-locking in fiber lasers, performing outstandingly in terms of pulse energy, repetition rate, pulse duration, and operating range in spectrum [13–21]. The fiber-based amplitude or phase modulation of the light using 2D materials has also been extensively studied. For example, optically excited carriers using an ultrashort optical pulse have been noted to modify the propagation loss of the signal beam in a tapered fiber coated with graphene to demonstrate the ultrafast all-optical switching [10, 22, 23]. An all-fiber graphene phase modulator based on the thermo-optic effect has also been suggested. Here, the light absorbed by the graphene layer

was found to increase the local temperature of the micro-fiber surrounded by graphene because of the photothermal effect, which subsequently modified the phase of the signal beam by changing the refractive index of the fiber through thermo-optic effect [11, 24].

Electro-optic modulation is the most widely used scheme in 2D material-based integrated optical modulators [7–9]. However, all-fiber electro-optic devices that evanescently interact with graphene were rarely explored so far, despite their potential advantages [25, 26]. Moreover, previous studies have shown limited performance, such as the narrow operational range in the spectrum (around 1550 nm) and the moderate modulation strength (~ 3 dB) [25]. Another work recently reported, based on graphene-coated photonic crystal fibers, exhibited a large modulation depth (~ 20 dB/cm at 1550 nm) over a broad spectral range of 1150–1600 nm [26]. However, since the end facet of the fiber was covered with ion liquid and graphene for electrical gating in the proposed device, it might not be easy to connect with the conventional fiber by fusion splicing, which can limit its advantages as an all-fiber device.

In this paper, we report an all-fiber device that evanescently interacted with graphene to achieve efficient electro-optical modulation over a broad spectral range. A side-polished fiber possessing high numerical aperture (NA) was used as a platform for a strong and robust evanescent field interaction with graphene. We found that a small mode-field area of the high NA fiber played a crucial role in enhancing the interaction between graphene and light with relatively low scattering losses. The electrolyte-based gating scheme was employed for further improving the graphene-light interaction, as well as efficiently tuning the Fermi-level of graphene. We successfully fabricated monolayer and bilayer graphene field-effect transistors on the side-polished high NA fiber and comprehensively investigated the layer-dependent optical and electrical properties of the devices over a broad spectral range. The device was observed to show the electro-optic absorption over nearly two-octave spans (532–1950 nm) with a strong modulation strength of up to 25.5 dB, where the spectral response of the device with applied gate voltage was in good agreement with the theoretical expectation.

2 Experimental results and discussion

2.1 Fabrication of the all-fiber graphene device

The all-fiber graphene device is schematically shown in Figure 1A. A high NA fiber (UHNA4, Nufern) embedded in a

Figure 1: (A) Schematic description of the all-fiber graphene device, (B) cross-sectional view of the calculated mode field distribution of the device, (C) photographic image of the fabricated device without ion liquid, and (D) optical microscope image of the side-polished section of the device (Inset: measured Raman spectrum of monolayer graphene).

quartz block with a curvature of 0.25 m was laterally polished, and the source, drain, and gate channels were deposited on the quartz block as shown in the figure. High-quality monolayer graphene grown using the chemical vapor deposition (CVD) method was then transferred to the polished section of the fiber, connecting the source and the drain channels. Afterward, a small droplet of ion liquid (EMIM-TFSI, Sigma-Aldrich) was applied to the device, covering the graphene and other electrode channels. The ionic liquid-based gating allowed adjusting the Fermi level of graphene over a wide range with an applied voltage of several volts. Figure 1B shows the numerically calculated cross-sectional view of the device at the polished section. The mode field area of the high NA fiber is approximately six times smaller than that of a standard single-mode fiber (SMF-28e, Corning), while the propagation loss of the fiber is negligible for the given device length. Thus, light can be efficiently confined in the vicinity of the graphene, enhancing the interaction with graphene and exhibiting low optical losses. Moreover, the ion liquid possessing a similar refractive index (1.42) as that of fiber cladding can increase the interaction with the graphene by extending the evanescent field of the guided mode to the surface of the polished fiber section [25]. A photographic image of the fabricated device is shown in Figure 1C. The red dotted line square indicates the transferred position of

the graphene with a size of $4 \times 3 \text{ mm}^2$ on the side-polished fiber. Figure 1D shows a microscopic image of the graphene at the side-polished fiber section, where the structure of the core and cladding of the high NA fiber are clearly visible. The measured Raman signal of the monolayer graphene is shown in the inset of Figure 1D. Nearly uniform Raman responses were observed over the whole graphene region, where the relative ratio of the 2D peak and the G peaks were measured to be approximately 2.78, indicating the monolayer nature of the transferred graphene. The bilayer graphene was prepared by stacking the CVD-grown large area monolayer graphene.

2.2 The optical and electrical response

When the gate voltage is close to the voltage at the charge neutral point (V_{CNP}) of graphene, optical transmission of the device is minimized due to the absorption of incident light by graphene through the interband transition. As the Fermi level of the graphene approaches the half of the incident photon energy, the light transmission gradually increases because the interband transition is not allowed by Pauli blocking [7]. Figure 2A compares the gate-tunable performance of the monolayer graphene device based on a standard SMF (SMF28e, Corning) and a high NA fiber. The optical response was recorded as a function of the applied gate voltage for incident light at a wavelength of 1550 nm with transverse electric polarization. In the figure, it can be clearly seen that the modulation depth (16.5 dB) of the device with a high NA fiber was significantly enhanced compared to that (3.2 dB) of the device with a standard SMF. We expect that the enhanced modulation depth mainly results from the tightly confined guided mode that interacts with the graphene in a high NA fiber. The insertion loss of the device with a high NA fiber was measured to be 2.5, 1.4 dB higher than that of the standard SMF-based

device (1.1 dB). Afterward, we studied the graphene layer-dependent property of the device fabricated with a high NA fiber. The V_{CNP} holding minimum conductivity was measured to be 1.66 and 0.87 V in the devices with monolayer and bilayer graphene, respectively. The positive V_{CNP} indicates that the graphene transferred on the quartz substrate is initially p-doped. Here, we defined the gate voltage at which the optical transmission becomes -3 dB at the maximum transmittance as the critical drive voltage (V_{CD}). Then, the voltage difference as $|V_{\text{CD}} - V_{\text{CNP}}|$ was measured to be 1.2 V in the device with monolayer graphene as shown in Figure 2B. For the device with bilayer graphene, the measured modulation depth was found to be 25.5 dB (10.2 dB/mm), the largest among the electrically gated all-fiber graphene devices reported. However, the voltage difference, $|V_{\text{CD}} - V_{\text{CNP}}|$, was observed to be 2.2 V, an increase of approximately 83% compared to the monolayer graphene. Thus, the modulation depth of the bilayer graphene device increases by 9.0 dB, but more gate voltage is required for the full optical modulation.

For further understanding of the performance of the device, we investigated the electrical response of the fabricated device. We measured the electrical transport properties of the graphene by monitoring the drain current as a function of the gate voltage applied to the device. Figure 3A and B shows the on-off ratio of drain current in monolayer and bilayer graphene devices, respectively, as a function of the applied drive voltage, V_D defined as $V_{\text{Gate}} - V_{\text{CNP}}$. The device with monolayer graphene shows a higher on-off ratio than that of the bilayer graphene device, which indicates that more carriers are induced at the monolayer graphene device for a given drive voltage. This trend is reasonably consistent with previous studies on the electrical transport properties of the few-layer graphene in large areas [27–29]. Moreover, the bilayer graphene is expected to share the charges with the distribution over the

Figure 2: Comparison between the optical responses of (A) monolayer graphene device with a standard single-mode fiber (SMF) and a high numerical aperture (NA) fiber and (B) monolayer and bilayer graphene devices with a high NA fiber as a function of applied gate voltage.

Figure 3: Measured electrical transfer characteristics as a function of applied drive voltage in (A) mono- and (B) bi-layer graphene devices. (C) Schematic representation of the charge distribution and Coulomb potential ϕ in bi-layer graphene with ion-liquid gating.

layers as shown in Figure 3C by screening effect, which results in the layer-dependent carrier doping for a given gate voltage, leading to the reduced carrier at the bottom layer graphene. We expect that the combined effect of reduced on-off ratio and screening effect in the bilayer graphene device requires a higher gate voltage to reach full optical modulation in Figure 2B.

2.3 Wavelength-dependent electro-optic properties of the device

In graphene, electrons act like massless Dirac fermions, and because of its linear bandgap nature, graphene exhibits universal light absorption ranging from visible to infrared. We investigated the optical characteristics of the devices over a broad spectral range, and Figure 4A displays the spectral response as a function of applied V_D to the device with monolayer graphene. Several discrete laser light sources from visible to mid-infrared (fiber-coupled diode-pumped solid state lasers [532 and 633 nm], fiber

Bragg grating-connected laser diodes [980, 1310, and 1550 nm], and a continuous wave fiber laser [1950 nm]) were used for the characterization. An electro-optic absorption change was observed over the spectral region ranging from 532 to 1950 nm for a given device, covering nearly two-octave spans, which is the broadest operational range in the spectrum among the reported all-fiber graphene devices. Our device with monolayer graphene showed the optical modulation strength of greater than 10 dB for the wavelength ranging from 980 to 1950 nm as shown in Figure 4A. Note that since our graphene device is initially p-doped, observation of optical transmission change by positive gate voltage is limited to long wavelengths. In the case of the bilayer graphene device, it was found that higher modulation strength (>15 dB) could be achieved in the same spectral range, but higher drive voltages were required, as shown in Figure 4B. As the Fermi-level of graphene changes in the p-doped direction, incident light with lower photon energy first experiences the Pauli blocking, which makes wavelength-dependent electro-optic modulation in graphene as schematically

Figure 4: Electro-optic response of (A) monolayer and (B) bilayer graphene devices as a function of applied drive voltage for several wavelengths of 532, 671, 980, 1310, 1550, and 1950 nm. (C) Schematic representation of Pauli blocking for light with different photon energy in graphene.

Figure 5: Wavelength-dependent electro-optic characteristics of the monolayer graphene device as a function of drive voltage. The red line is calculated value and the squared dots are obtained from experiment.

expressed in Figure 4C. We also calculated the maximum change rate of the optical transmission, defined by dT/dV_D for several wavelengths. The calculated values of dT/dV_D were 45.3, 74.9, 92.4, and 286%/V for the wavelengths of 980, 1310, 1550, and 1950 nm, respectively, in the monolayer graphene device. Thus, the optical transmission change for a given drive voltage was found to be more efficient toward longer wavelengths.

The maximum optical transmission change occurred at $\hbar\omega = 2E_F$, where $\hbar$ is the Planck constant, ω is the angular frequency of light, and E_F is the Fermi energy of graphene. In the graphene-based gating device, the relation between the charge carrier density n , E_F , and V_D is described as $V_D = E_F/e + ne/C_{EDL}$ [30], where e is the electron charge. The Fermi energy is also expressed as $E_F = \hbar|v_F|\sqrt{\pi n}$ in graphene, where v_F is the Fermi velocity. The fitting results based on the equations mentioned above, which is in good agreement with the measured spectral response (Figure 5), especially for the high optical modulation region. Parameters used for the fitting were $v_F = 1.1 \times 10^6$ m/s and $C_{EDL} = 2.1 \mu\text{F}/\text{cm}^2$, which agrees to the previously reported values in a reasonable range [28–30].

3 Conclusion

In summary, we report that an all-fiber graphene device exhibited strong electro-optical absorption over a broad spectrum ranging from visible to near-infrared. The optical device based on side-polished high NA fiber showed a strong light-matter interaction with monolayer and bilayer graphene. We fabricated an ion liquid-based gating device onto the side-polished fiber, where the electro-optic absorption was observed in the wavelength ranging from 532 to 1950 nm. The device fabricated with monolayer

graphene shows the electro-optic response in a broader spectrum at a smaller gate voltage than that with bilayer graphene but has a lower modulation depth (16.5 dB) than the bilayer device (25.5 dB). The gate voltage required to control the optical transition over the broad spectral range was found to be reasonably similar to the theoretically expected value based on the bandgap dispersion of the graphene. Particularly, our device exhibited more efficient electro-optic modulation at a longer wavelength region, where the maximum light modulation efficiency of 286.3%/V was achieved at the wavelength of 1950 nm. The strong light-graphene interaction over the broad spectral range presented in this study could be used to realize efficient graphene devices, such as broadband all-fiber photodetectors and electrically tunable in-line nonlinear saturable absorbers with a large modulation depth. In addition, the proposed fiber-based configuration will provide an efficient platform for studying and utilizing new emerging 2D materials.

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