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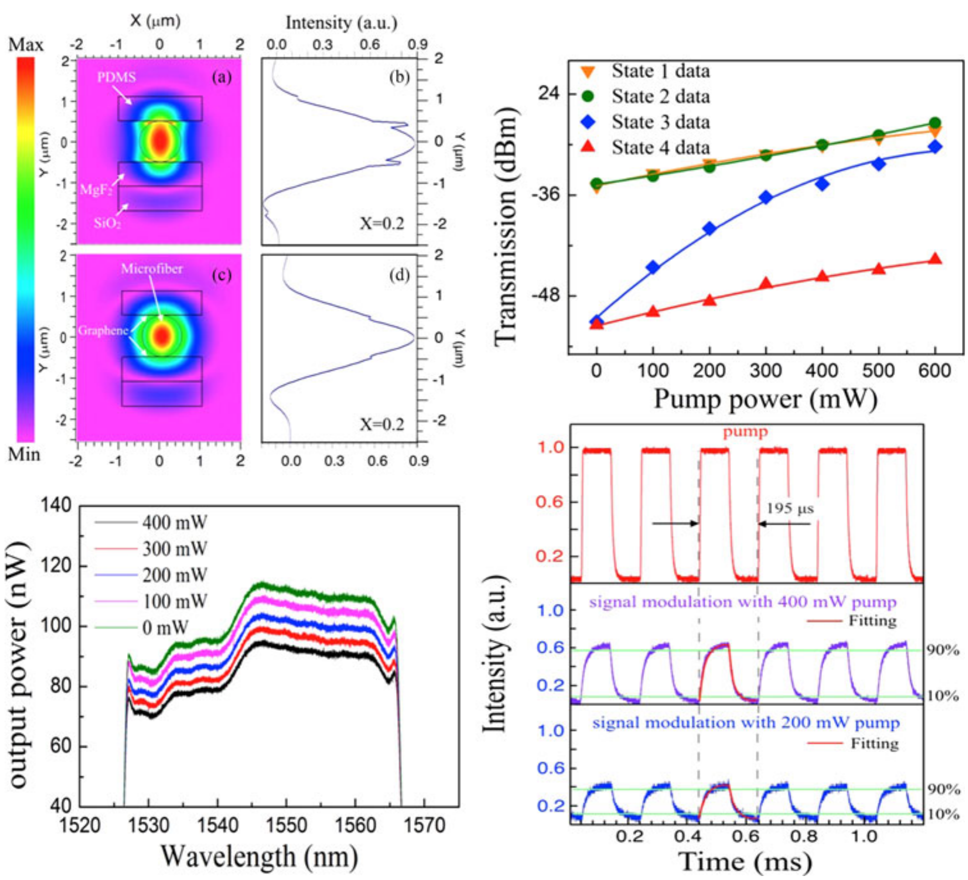
Ruiduo Wang
Diao Li
Hao Wu
Man Jiang
Zhipei Sun
Yonghui Tian
Jintao Bai
Zhaoyu Ren



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All-Optical Intensity Modulator by Polarization-Dependent Graphene-Microfiber Waveguide

Ruiduo Wang,[1] Diao Li,[1] Hao Wu,[1] Man Jiang,[1] Zhipei Sun,[2] Yonghui Tian,[3] Jintao Bai,[1] and Zhaoyu Ren [1]

[1]State Key Lab Incubation Base of Photoelectric Technology and Functional Materials, International Collaborative Center on Photoelectric Technology and Nano Functional Materials, School of Physics, Institute of Photonics & Photon Technology, Northwest University, Xi'an 710069, China
[2]Department of Electronics and Nano engineering, Aalto University, Espoo FI-02150 Finland
[3]Institute of Microelectronics and Key Laboratory for Magnetism and Magnetic Materials of Ministry of Education, School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China.

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Abstract: We demonstrated all-optical intensity modulator based on polarization-dependent graphene-covered microfiber (GMF) waveguide. By controlling the polarization mode of incident light, a greatly adjustable enhanced interaction between the propagating light and the graphene can be obtained via the evanescent field of the microfiber. By employing 980-nm pump light and 1550-nm signal light in continuous wave, the strong light–graphene interaction enables a maximum modulation depth of $\sim$20.86 dB, and by pumping 980 nm wave pulses, we obtained the temporal response characteristics of signal light with modulation rate of 5.13 kHz. This all-optical intensity modulator is compatible with optical fiber systems, and features with ease of fabrication, and steerable high modulation depth, which show potential in graphene's applications such as all-optical switching and all-optical communications.

Index Terms: Photonic materials, fiber optics systems, waveguide devices.

1. Introduction

Optical intensity modulators are crucial photonic devices in a variety of photonic applications, such as communications, signal processing, cross-phase modulation, sensing, pulse generation [1]–[6]. Particularly, all-fiber integrated intensity modulators are particularly desirable configurations for fiber based applications, which have been intensively developed and several applications have been addressed, for example, passive saturable absorbers (SAs) and active electro-optic polymer based intensity modulators have been intensively developed in past decades, which show advantages due to its low cost and feasibility of remote operation [7], [8]. Compared with these techniques, all-optical method is advantageous because of simple implementation and low cost. Compared with traditional materials, two–dimensional (2D) materials are favorable for optical applications. Graphene is a 2D material with a single atomic layer of carbon atoms arranged in a hexagonal lattice, which has been extensively researched due to its unique physical properties [9], [10] and nonlinear effects such as saturable absorption, Kerr effect, [1], [11], [12], and broadband uniform absorption coefficient (around 2.3% over a wide spectral range from the visible to the infrared [13], [14]). Based on the high flexibility and strong optical absorption, graphene can be coupled with waveguides such as microfiber and silicon based waveguide to realize light-matter interaction [15]–[17] and accomplish the optical modulation, several applications have been addressed, such as the all-optical fiber modulator based on a stereo graphene–microfiber structure (GMF) utilizing the lab-on-rod technique, and a modulation depth of ∼7.5 dB (∼2.5 dB) were demonstrated for two polarization states [18], the ultrafast all-optical modulator by GCM structure response time of ∼2.2 ps [15], and broadband all-optical modulation depth with maximum modulation depths of 5 dB and 13 dB for single-layer and bi-layer graphene, respectively [19]. However, for intensity modulator, it is remaining a challenge to improve the modulation depth.

In this letter, we propose a polarization-dependent method and applied in all-optical intensity modulation system by graphene covered microfiber (GMF) to research graphene assisted intensity modulator with high modulation depth, which has barely been reported. Polarization-based research is essential in several addressed optical applications, including rotator, quantum logic gate, interference filters and polarization switch acousto-optic polarization coupler [20]–[24]. In fiber system, the light's polarization mode is adjustable by employing polarization controller (PC), which methods can effectively control light-graphene interaction [25], [26], thus the polarization-dependent optical absorption of graphene would show potential in optical modulation with high modulation depth. We use a 980 nm laser as a pump light to modulate the intensity of a 1550 nm signal light when coupling into the GMF, and polarization mode of incident lights were switched between TM and TE mode by two PCs. The results demonstrated a strong polarization-dependent absorption with adjustable modulation depth varies from 6.65 dB to 20.86 dB under 600 mW pump. In addition, the research on temporal response characteristics of GMF intensity modulator achieved modulation rate of 5.13 kHz by pumping 980 nm chopped square wave pulses. Our polarization-dependent method introduced an easily controlled way to realize large all-optical modulation at near infrared region, which is a promising technique in optical signal processing for telecommunications services.

2. Setup and Device Fabrication

To make GMF, a microfiber was first fabricated by stretching a standard telecommunication single-mode fiber with flame heating. Optical microscopic measurement confirmed that the stretched area was a uniform cylinder with a diameter of ∼6.3 μm and length of ∼8 mm. Monolayer graphene film was synthesized on a copper foil by chemical vapor deposition (CVD) method [27]. Free standing graphene film with large size (∼0.96 cm^2) was obtained after etching away the copper substrate by 15% ferric chloride solution [28]. Since the atomically layered graphene are mechanically robust and naturally passivated on surface, they can be reliably and firmly integrated into other structures. We covered the microfiber by two planar graphene films in a parallel layout, the bottom graphene film was transferred on a MgF_2 (n∼1.38, to reduce interface loss) coated silicon wafer to support the microfiber. glue was then dropped on the substrate to fix the microfiber. Owing to graphene's atomically thin structure, its highly flexibility enables to be incorporated with other photonic structures [29]–[31], a polydimethylsiloxane (PDMS) membrane supported graphene film was coated on top of the microfiber to form a sandwiched structure, as shown in Fig. 1(a), which radial microscopic images is shown in the Fig. 1(b).

Fig. 1(a) illustrates a schematic setup of the optical intensity modulation. A 980 nm laser diode (LD) was used as the pump laser, and the counterpart light (i.e., the signal light) was a telecommunication laser centered at 1550 nm (with linewidth of 200 kHz, 20 mW), two PCs were connected to the output ports of the pump light and signal light to control the polarization mode distribution before the light propagating into the GMF. The operation lights were coupled into the GMF through a 980/1550 nm wavelength division multiplexer (WDM) for modulation. A tunable filter (Tunable

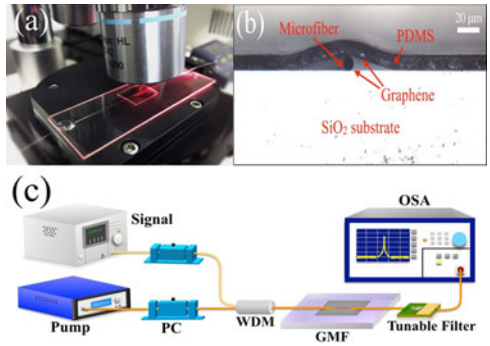

Fig. 1. (a). A GMF fixed on the adjustable stage of an optical microscope. (b). Radial profile of the fabricated GMF taken by optical microscope. The microfiber is sandwiched with two graphene sheets, the SiO_2 substrate is coated by MgF_2 layer with 0.6 μm thickness. (c). Schematic of the polarization controlled intensity modulation experiment.

wavelength of 1530–1570 nm, passband of 1 nm) was connected to the output end of the GMF to extract the transmitted signal light, and finally detected the spectrum by optical spectrum analyzer (OSA).

3. Experimental Results and Analyses

3.1 Numerically Simulation

To achieve adjustable high modulation depth in the context of polarization control, we employed weak bending properties of PDMS (covered with a hard plastic layer, avoid faying the surface shape), which was characterized by a gap formed between the top and bottom films when covering PDMS graphene film on microfiber, instead of wrapping graphene on fiber surface, therefore, by adjust the evanescent-field distributions by controlling the polarization direction of light, the goal of changing graphene-light interaction was achieved. We numerically analyzed the radial light transmission distribution of the GMF's transverse electric (TE) mode and transverse magnetic (TM) mode with Rsoft method. In this experiment, the transmission mode of light can be easily switched between TE and TM mode by adjusting PC. Close contact of graphene films with the microfiber assures effective interaction regardless the beam polarization direction. The thicknesses of the media were assumed as 1 μm for the PDMS, 0.335 nm for graphene, 0.6 μm for MgF_2 and SiO_2 substrates. Fig. 2(a) and (c) show the distribution of TM mode and TE mode electric-field vector, respectively [32]. Fig. 2(b) and (d) depict the relationship between Y coordinates (the value corresponding to Y coordinates in Fig. 2(a) and (b)) and intensity distributions of TM mode and TE mode separately, the results shown that the intensity of graphene covered area in TM mode ($Y = 0.5\,\mu$m and $-0.5\ \mu$m) is obviously higher than of TE mode. Therefore, tuning PC and switching light to TM mode can induce stronger light-graphene interaction and absorption, which is favorable to achieve larger modulation. This simulation inferred that the total absorption can be controlled by changing the mixture of TM and TE modes, provided a polarization-dependent intensity modulation.

3.2 Results and Analyses

To study the modulation by polarization-dependent effect, we firstly removed two PCs from system and measured the transmitted spectrum of the signal light, which was pumped by different powers (between 0 mW to 200 mW), as shown in Fig. 3(a). The transmitted spectral intensity increased significantly as rising the pump power, and the transmitted signal power measurement was then measured in the pump light power range from 0 mW to 600 mW. The eventual result presented a modulation depth of 6.62 dB. In order to confirm that the intensity modulation was solely caused by graphene, we designed a comparison experiment by replacing the GMF device with a PDMS

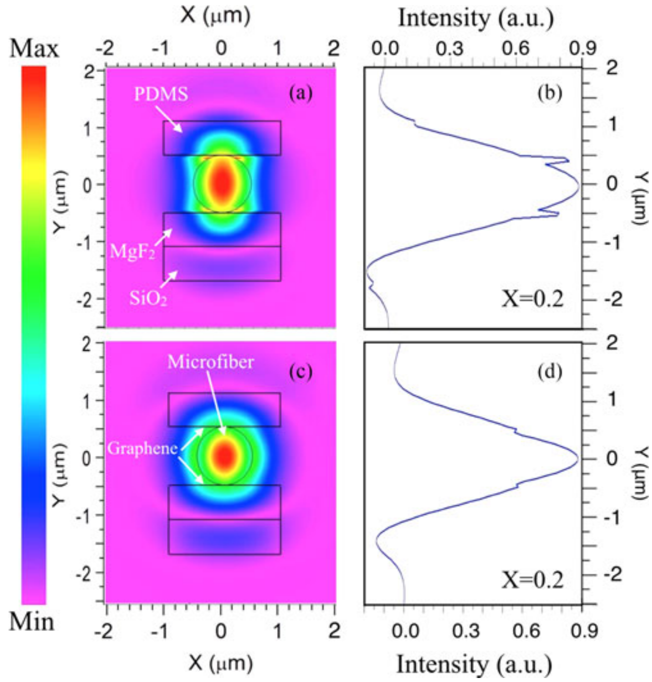

Fig. 2. (a). Numerical simulation of the radial distribution of the TM mode propagating along GMF. (b). Relationship between Y coordinates and intensity distributions of TM mode. (c). Numerical simulation of the radial distribution of the TE mode propagating along the GMF. (d). Relationship between Y coordinates and intensity distributions of TE mode.

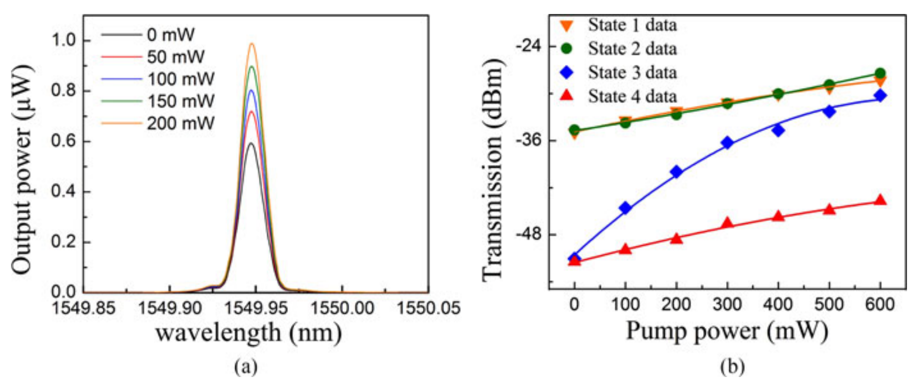

Fig. 3. (a). Spectra of signal light as a function of the pump power. (b). The fitting curve of four transmission states, corresponding to Table 1, respectively.

covered microfiber on the same substrate without graphene films, only 0.44 dB transmission variation was obtained when the pump light power varies in the same span, which can be explained by the possible thermo-optic effect induced refractive index variation in the silica microfiber [26]. Compared with the graphene-assisted intensity modulation, this effect is so weak that we would omit it in the next discussion.

We then connected two PCs on the output ports of 980 nm pump light and 1550 nm signal light, as shown in Fig. 1(a). The numerically simulation results proved that the transmittance can be switched between TE and TM modes by tuning PCs in the context of polarization controlled light-graphene interaction. High precision power meter was used to monitor the transmissions of pump

TABLE 1

Transformed the Weak and Strong Light-Graphene Interaction of Pump and Signal Source by Turning Two PCs, The Respective Interaction Effect Combined Into Four States, With Pump Power Increasing to 600 mW, The Corresponding Modulation Depth of Signal Light is Shown.

Light-graphene interaction state (modulation depth) interaction effect	1550 nm weak interaction (TE mode)	1550 nm strong interaction (TM mode)
980 nm strong interaction (TM mode)	State 1 (6.65 dB)	State 3 (20.86 dB)
980 nm weak interaction (TE mode)	State 2 (7.24 dB)	State 4 (7.74 dB)

light and signal light after propagating along GMF. The highest transmittance is a result of weakest light-graphene interaction and optical absorption, corresponding to TE mode. Reversely, TM mode results in lowest transmittance because of strongest light-graphene interaction and optical absorption. These results indicated polarization-dependent properties of our GMF device. By selecting TM and TE mode, we designed four states of modulation system which enables strong or weak light-graphene interactions to be steerable. During these four states, we measured the transmission of modulated signal with 0-600 mW pump, which tendency was found to increase monotonously, as plotted in the Fig. 3(b). The highest modulation depth under four states all displayed at 600 mW pump power. The details and corresponding modulation depths were shown in Table 1.

In state 1 and state 2, the signal light showed high transmission in case of without pump light. This is due to the minimal interaction between the TE mode and the graphene sheets. Two fitting curves were approximately overlapped, which illustrated that the responses of signal transmittance were not sensitive to pump power. We attributed this to the weak absorption by graphene sheets. However, in state 3 and state 4 (i.e., the maximal interaction between TM mode and graphene sheets), we noticed distinct high absorption induced attenuation in the condition of without pump light. In state 4, (i.e., graphene's weakest absorption) the signal's transmittance showed little relationship with pump power variation. This accounts for the results of low modulation depth of 7.74 dB. As for state 3, TM mode of pump beam was drastically absorbed by graphene to excited more carriers to condition band, which significantly reduced graphene's absorption to signal light, means light-induced transparent effect. This process interprets the signal's positive modulation response as function of pump power resulting in a high modulation depth of 20.86 dB. In addition, we applied a slight external force to PDMS graphene film by fine-tuning system, which decreased the gap between the top and bottom graphene films, by detecting the signal's transmission power with 0–600 mW pump power, the results shown the decrease of polarization-dependent properties, and larger graphene-microfiber contact area induced higher interaction, shown higher transmission loss, whereas the modulation depth in same state was approximately unchanged.

To investigate whether the polarization state of the pump light influences the optical modulation to signal light, we adjusted the PC and monitored intensity before GMF, no obvious distinguishing transmittance were detected. Then replaced GMF by employing no graphene microfiber covered by bare PDMS, tuned PC and tested intensity of signal, measured a minute modulation range from 24.08 dBm to 24.57 dBm, which can be omitted, proved that effective modulation was induced by graphene assisted methods. By GMF device, compared to no PC assisted modulation system's 6.62 dB modulation depth, polarization assisted system showed evident higher effect of 20.86 dB, and transmission intensity can be easily modulated between maximum and minimum by tuning two PCs.

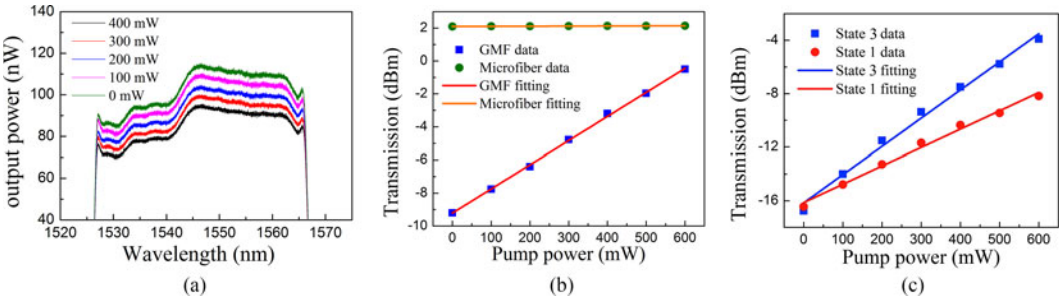

Fig. 4. (a). ASE broadband laser's transmission spectrum as pump power linearly increased from 0 mW to 400 mW. (b). Without PC in the setup, the intensity transmission of the broadband signal light of GMF and the bare PDMS covered microfiber is plotted in red and yellow lines, respectively. (c). With PCs in the setup, state 1: strong pump-graphene interaction in TM mode and weak signal-graphene interaction in TE mode. The measured data was shown in red line. State 2: Strong pump-graphene interaction in TM mode and high signal-graphene interaction in TM mode, the data was shown in blue line.

3.3 Polarization Controlled Broadband Optical Modulation

Based on the proposed modulation experiment, we implemented a broadband all-optical intensity modulation with GMF's polarization-dependent absorption. We first employed amplified spontaneous emission (ASE) spectrum (operating wavelength in the span of 1527 nm–1565 nm with output power of 10 dBm) and 980 nm pump light to input into the setup in the case without PCs. A 980/1550 nm WDM was inserted at GMF's output port to split pump and signal. The results show that the transmitted signal intensity was linearly increased in the broadband spectral range as the pump power varies in the range of 0-400 mW. The monitored spectrum of the signal was shown in Fig. 4(a). To confirm the modulation was from graphene, we compared the transmission of signal light after propagating through the GMF, bare PDMS covered microfiber. The results are depicted in Fig. 4(b). As can be seen, the modulation depth of GMF was calculated to be 8.7 dB in the pump power range between 0 to 600 mW. For the bare PDMS covered microfiber, the transmission changed from 2.1 dBm to 2.14 dBm, which can be omitted as explained in previous section. Afterwards, we connected two PCs on the output ports to switch the polarization state between TM and TE modes. Graphene's absorption was sensitive to polarization mode, and we correspondingly detecting broadband signal transmission, four states of modulation system as shown in Table 1 were still effective, after switching on the pump light, all states showed an output intensity variation. The modulation depths of state 1 (980 nm in TM mode, 1550 nm in TE mode) and state 2 (980 nm in TM mode, 1550 nm in TM mode) were measured to be 8.26 dB and maximum of 12.86 dB, as shown in Fig. 4(c). The TM mode of pump light induced high transmittance, which means the signal light was independent to pump power. In contrast, higher modulation depth in state 2 was mainly determined by strong interaction of signal light TM mode with graphene. This proves that the modulation depth can be obviously improved with TM mode interaction due to the strong interaction, which shown strong light-induced transparent effect. Our results demonstrated that the modulation depth can be adjusted by controlling polarization mode between TM and TE modes.

3.4 Temporal Response of Intensity Modulation

Based on the modulation system, we studied the temporal response characteristics of GMF intensity modulator, a pair of collimators were connected to the output port of 980 nm laser diode to generate spacial beam area along the beam, this allows to insert a chopper to switch the CW pump light to square wave pulse (operation frequency of 20 Hz–5.2 kHz), which installed between collimators, and fixed the signal at 1550 nm, we select the minimum data of signal light (appeared with no chopper light) to be zero, and the data were given normalized treatment, the modulation results are shown in Fig. 3(c). The pump light was switched to square wave with a period of 195 μs. The modulated 1550 nm signal light was measured to be synchronized with the pump pulses. The modulated pulse in the

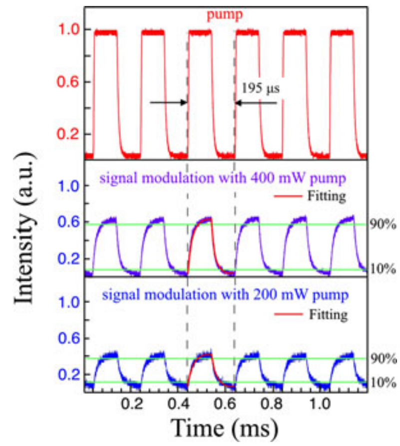

Fig. 5. Signal modulation results by 980 nm square wave pulse. Blue waveform depicts the signal modulated by 200 mW pump, violet waveform depicted the signal modulated by 400 mW pump.

signal was observed when the pump power rises to 20 mW, corresponding to a modulation rate of 5.13 kHz. The rising and falling time of signal [16] were calculated to be 18 μs/17 μs, respectively. The time range from 10% to 90% of the rising and falling edge is normally defined in signal processing, and as shown in green lines in Fig. 5. Here, we calculated the 10%–90% rising/falling time to be 39/39 μs, which theoretically matched 2.2 times the corresponding exponential time constant. Compared with 200 mW square wave pump pulse, the 400 mW pump pulse can more effectively reduce the signal's absorption by graphene, which enables higher transmission. By verifying the intensity modulation mechanism in Fig. 3, we proved that our modulator can be applied in fast temporal response. In the experiments, the polarization-dependent properties of GMF enables to change the modes between TM and TE by adjusting the PCs.

4. Conclusion

In conclusion, we designed a fiber all-optical intensity modulation system assisted by two graphene films covered microfiber device. The gap between top and bottom graphene films in our GMF enables modified polarization state between TM and TM mode of both pump and signal light by turning PCs. This polarization-dependent method can powerfully change the light-graphene interaction, corresponding to enhanced modulation depth of both tunable signal and ASE broadband signal by pumping 980 nm light. 1550 nm signal light under four polarization-dependent states, the modulation depth of signal intensity increased from 7.24 dB to 20.86 dB by 600 mW pump. Compared to no PC system and employing same devices, obvious higher modulation depth was shown. Pumping ASE broadband signal light under four polarization-dependent states, the intensity modulation depth increased from 8.26 dB to 12.86 dB. Using above two signal lasers in this system, under random constant pump power, by turning PC, the modulation depth would be continuous adjustable through changing polarization state between TE and TM mode. We did comparison experiments using bare microfiber to repeat, the extreme weak results illustrated graphene's modulation ability. By chopper installed in transmission path of pump light with frequency of 5.13 kHz, the GMF device showed a considerably fast response, the 10%–90% rise/fall time is 39/39 μs, and by 400 mW pump power, apparent higher transmission was obtained. Considering the simplicity of GMF's fabrication and all-fiber method, low cost, low power requirement, and continuous adjustable high amount of intensity modulation depth, this modulation system can also be incorporated into other fiber devices to extend their applications. Therefore, the work will open the door for graphene's realistic applications in all-optical signal processing.

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