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High extinction ratio D-shaped fiber polarizers coated by a double graphene/PMMA stack

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Abstract: We demonstrate theoretically and experimentally a high extinction ratio and compact size TE-pass polarizer made by a D-shaped fiber coated with a double graphene/PMMA stack. The light propagating in the core of the fiber can be efficiently coupled into the graphene sheet thanks to the giant enhancement of the modal evanescent field associated with the high refractive index graphene/PMMA cladding. The strong interaction between the light and graphene produces a large attenuation difference between modes with orthogonal polarizations, resulting in an improved extinction ratio and a reduced insertion loss due to the device compactness. A double graphene/PMMA stack coated polarizer with an extinction ratio of up to 36 dB and an insertion loss of 5 dB has been achieved when the device length is only 2.5 mm. The double graphene/PMMA stack has proved to be significantly better than single graphene/PMMA stack and bilayer graphene/PMMA structures, providing a polarizer with maximum extinction ratio of 44 dB for a length of 4 mm. The achieved results indicate that the proposed high extinction ratio polarizer is a promising candidate for novel in-fiber graphene-based devices.

OCIS codes: (060.2340) Fiber optics components; (230.5440) Polarization-selective devices; (060.2420) Fibers, polarization-maintaining; (060.0060) Fiber optics and optical communications.

References and links

1. V. Kozlov, J. Nuño, J. D. Ania-Castañón, and S. Wabnitz, "Theoretical study of optical fiber Raman polarizers with counter propagating beams," J. Lightwave Technol. **29**(3), 341–347 (2011).
2. R. A. Bergh, H. C. Lefevre, and H. J. Shaw, "Single-mode fiber-optic polarizer," Opt. Express **20**, 5652–5657 (2012).
3. X. Yin, X. Ke, L. Chen, T. Zhang, J. Li, Z. Zhu, and X. Li, "Ultra-broadband TE-pass polarizer using a cascade of multiple few-layer Graphene embedded silicon waveguides," J. Lightwave Technol. **34**(13), 3181–3187 (2016).
4. J. T. Kim and C. G. Choi, "Graphene-based polymer waveguide polarizer," Opt. Express **20**(4), 3556–3562 (2012).
5. N. K. Chen and S. Chi, "Influence of a holey cladding structure on spectral characteristics of side-polished endlessly single-mode photonic crystal fibers," Opt. Lett. **31**(15), 2251–2253 (2006).
6. Y. V. Bludov, M. I. Vasilevskiy, and N. M. R. Peres, "Tunable graphene based polarizer," J. Appl. Phys. **112**(8), 084320 (2012).
7. K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos, and A. A. Firsov, "Two-dimensional gas of massless dirac fermions in graphene," Nature **438**(7065), 197–200 (2005).
8. F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," Nat. Photonics **4**(9), 611–622 (2010).
9. T. Mueller, F. Xia, and P. Avouris, "Graphene photodetectors for high speed optical communications," Nat. Photonics **4**(5), 297–301 (2010).
10. S. Y. Choi, D. K. Cho, Y. W. Song, K. Oh, K. Kim, F. Rotermund, and D. I. Yeom, "Graphene-filled hollow optical fiber saturable absorber for efficient soliton fiber laser mode-locking," Opt. Express **20**(5), 5652–5657 (2012).

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11. N. H. Park, H. Jeong, S. Y. Choi, M. H. Kim, F. Rotermund, and D. I. Yeom, "Monolayer graphene saturable absorbers with strongly enhanced evanescent-field interaction for ultrafast fiber laser mode-locking," Opt. Express **23**(15), 19806–19812 (2015).
12. T. Chen, H. F. Chen, and D. N. Wang, "Graphene saturable absorber based on slightly tapered fiber with inner air-cavity," J. Lightwave Technol. **33**(11), 2332–2336 (2015).
13. S. Yu, X. Wu, K. Chen, B. Chen, X. Guo, D. X. Dai, L. Tong, W. T. Liu, and Y. R. Shen, "All-optical graphene modulator based on optical Kerr phase shift," Optica **3**(5), 541–544 (2016).
14. M. Liu, X. Yin, and X. Zhang, "Double-layer graphene optical modulator," Nano Lett. **12**(3), 1482–1485 (2012).
15. B. C. Yao, Y. Wu, A. Q. Zhang, Y. J. Rao, Z. G. Wang, Y. Cheng, Y. Gong, W. L. Zhang, Y. F. Chen, and K. S. Chiang, "Graphene enhanced evanescent field in microfiber multimode interferometer for highly sensitive gas sensing," Opt. Express **22**(23), 28154–28162 (2014).
16. Q. Bao, H. Zhang, B. Wang, Z. Ni, C. H. Y. X. Lim, Y. Wang, D. Y. Tang, and K. P. Loh, "Broadband graphene polarizer," Nat. Photonics **5**(7), 411–415 (2011).
17. C. Y. Guan, S. Q. Li, Y. Z. Shen, T. T. Yuan, J. Yang, and L. B. Yuan, "Graphene coated surface core fiber polarizer," J. Lightwave Technol. **33**(2), 349–353 (2015).
18. N. Luan, R. Wang, W. Lv, and J. Yao, "Surface plasmon resonance sensor based on D-shaped microstructured optical fiber with hollow core," Opt. Express **23**(7), 8576–8582 (2015).
19. H. J. Zhang, N. Healy, L. Shen, C. C. Huang, N. Aspiotis, D. W. Hewak, and A. C. Peacock, "Graphene-based fiber polarizer with PVB-enhanced light interaction," J. Lightwave Technol. **34**(15), 3563–3567 (2016).
20. K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, "Electric field effect in atomically thin carbon films," Science **306**(5696), 666–669 (2004).
21. J. Horng, C. F. Chen, B. Geng, C. Girit, Y. Zhang, Z. Hao, H. A. Bechtel, M. Martin, A. Zettl, M. F. Crommie, Y. R. Shen, and F. Wang, "Drude conductivity of Dirac fermions in graphene," Phys. Rev. B **83**(16), 165113 (2011).
22. F. H. L. Koppens, D. E. Chang, and F. J. García de Abajo, "Graphene plasmonics: a platform for strong light-matter interactions," Nano Lett. **11**(8), 3370–3377 (2011).
23. S. A. Mikhailov and K. Ziegler, "New electromagnetic mode in graphene," Phys. Rev. Lett. **99**(1), 016803 (2007).

1. Introduction

Optical polarizers [1, 2] are important passive devices for selecting the polarization of electromagnetic waves and are widely applied to characterize the polarization state or phase of optical systems. Compared with conventional polarizers [3, 4], in-fiber polarizers [5, 6] have several advantages such as small size, low insertion loss and easy integration into optical fiber systems. Recently, graphene [7–9] has attracted enormous attention due to its unique electronic and photonic properties, including strong nonlinearity, high carrier mobility, ultrafast broadband response, high efficiency for light-matter interaction, and high thermal conductivity. Graphene-based structures have been exploited to realize saturable absorbers of fiber lasers [10–12], all-optical modulators [13, 14], sensors [15] and broadband polarizers [16]. As far as polarizers are concerned, owing to the linear dispersion of Dirac electrons, graphene can selectively support TE or TM surface plasmon mode [16–18]. A broadband graphene polarizer with an extinction ratio of ~27 dB and a high insertion loss of ~15 dB was demonstrated in a D-shaped fiber (DF) [16], which required monolayer graphene with propagation distance of 3.5 mm. Graphene-based surface core/side-polished fiber polarizers [17, 19] rely on the high refractive index of buffer films covered on the graphene, which lead to a large attenuation difference between the two orthogonal polarizations. The graphene-based side-polished fiber polarizer with 1 μm thick PVB buffer has an extinction ratio of 37.5 dB, however, it required a monolayer graphene with long propagation distance of ~1cm and an ultra-smooth polished surface with a roughness of <1 nm RMS [19], which will increase the difficulty of device preparation. Therefore, it is desirable to obtain an optical fiber polarizer with compact size and low insertion loss.

In this work, we propose a DF TE-pass polarizer coated by a double graphene/polymethyl methacrylate (PMMA) stack. By introducing PMMA, the semimetal property of graphene is greatly enhanced and the field distribution in the direction perpendicular to the graphene layer is broadened so that more energy is coupled into the graphene films. A 2.5 mm-long double graphene/PMMA DF polarizer has been realized and shows a good performance with an extinction ratio up of ~36 dB and a low insertion loss of ~5 dB at 1590 nm.

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2. Design and theoretical calculations

Figure 1(a) shows the schematic of a single graphene/PMMA stack coated DF, where a monolayer graphene and a PMMA film are sequentially deposited on the polished surface of the DF. The attenuation of two orthogonal polarizations within the D-shaped area are different due to graphene unique physical properties. The strength of the light-matter interaction is enhanced by adding a high refractive index material PMMA upon the graphene sheet. In order to achieve an even higher extinction ratio, another a graphene/PMMA stack is added, as shown in Figs. 1(b), 1(c) and 1(d). The advantage of the proposed device is that the TM mode can be coupled more efficiently into the graphene film to be absorbed [17]. In the following calculations, the wavelength is $\lambda = 1550$ nm, h denotes the PMMA thickness and L_g is the graphene length (i.e. propagation length). The PMMA layer has a refractive index of $n = 1.49$, which is higher than that of fiber core ($n_1 = 1.455$) and cladding ($n_2 = 1.450$). The side-polished fiber can be fabricated by removing a portion of the cladding of a single mode fiber (SMF), which has cladding and core diameters of $D_{cladding} = 125$ μm and $D_{core} = 9$ μm, respectively. The polishing depth d is defined as the distance between the initial surface and the polished plane and it has a great effect on the extinction ratio. The uniform D-shaped region forms the interaction window and can provide a platform to create a variety of optical devices.

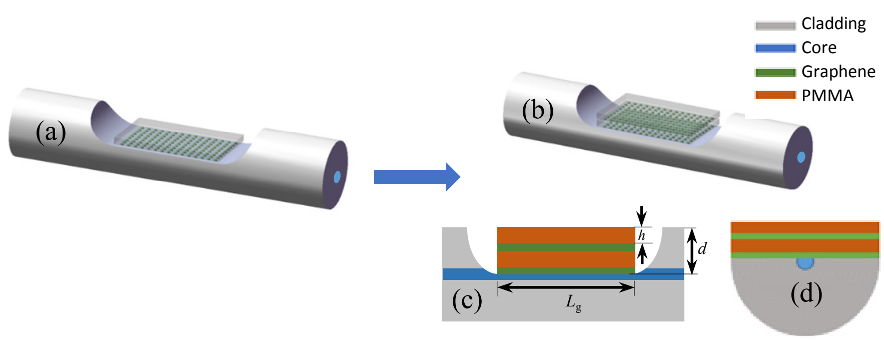

Fig. 1. D-shaped fiber coated by (a) single graphene/PMMA stack and (b) double graphene/PMMA stack. (c) Longitudinal profile and (d) cross-section of the proposed polarizer.

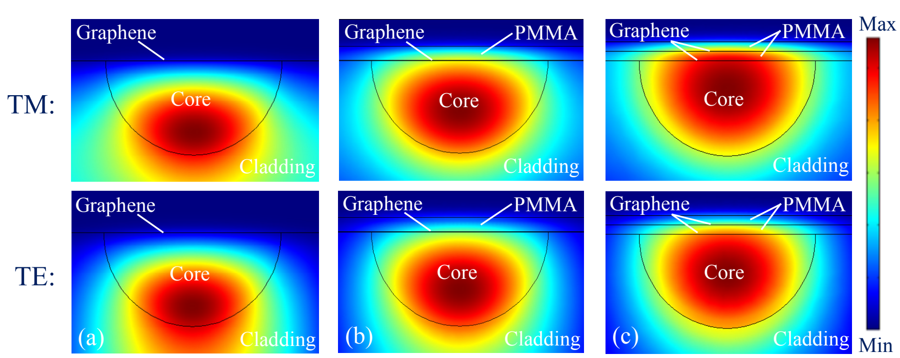

Fig. 2. The electric field distributions of TM/TE modes of DF polarizers covered with (a) a monolayer graphene, (b) a single graphene/PMMA stack and (c) a double graphene/PMMA stack. The PMMA thickness is $h_{PMMA} = 700$ in (b) and 400 nm in (c).

The finite element method (FEM, COMSOL) was used to determine how the graphene and PMMA sheets modulate the propagation of light along the D-shaped fiber. In the simulation, graphene layer is modeled as a transition boundary condition with complex dynamic conductivity and its chemical potential is set to 0.1 eV, which is typical order for monolayer graphene [20–22]. The conductivity of the graphene sheet has a large negative imaginary component at chemical potential of 0.1eV so that the interband transition dominates the absorption [23]. The weakly damped TE mode is supported by graphene, while the TM mode is absorbed by the graphene, resulting in a TE-pass polarizer. Figure 2 shows the electric field distributions of the TM/TE modes in side-polished fibers coated with a graphene monolayer, a graphene/PMMA single stack and a graphene/PMMA double stack. The high refractive index PMMA layer clearly has a strong effect on the mode field distribution. The graphene/PMMA double stack can move the mode center closer to the graphene layer, further enhancing the graphene-light interaction. The dependences of the confinement loss of TE and TM modes on the thickness of PMMA and the polishing depth of the fiber are investigated in the DFs covered by single graphene/PMMA stack as shown in Fig. 3(a). Although the loss of both TE and TM modes become larger for increasing PMMA thicknesses and polishing depths, the loss of the TE mode is much smaller than that of the TM mode and thus its loss can be ignored. With increasing polishing depth, the core guided mode becomes leaky for both polarizations, which will result in a large loss. Therefore, the polishing depth is selected to be ~62.5 μm to achieve an optimum performance, which also guarantees that the fiber core holds the largest interaction area with the graphene sheet. Similarly, the dependence of the confinement losses of TE and TM modes on the thickness of PMMA in the DFs covered by double graphene/PMMA stacks are shown in Fig. 3(b), where the polishing depth is ~62.5 μm. It is worth pointing out that the energy of the propagating mode is coupled into the PMMA layer rather than in the graphene sheet once the thickness of PMMA is large, thus, the PMMA thickness should be optimized for each selected structure. In the single and double stacks DF polarizers the PMMA thickness is h_{PMMA} = 700 nm and 400 nm, while the corresponding loss difference between TE and TM modes is 5.1 dB/mm and 16 dB/mm, respectively. The extinction ratio of the double stack is approximately 3 times higher than that of the single stack.

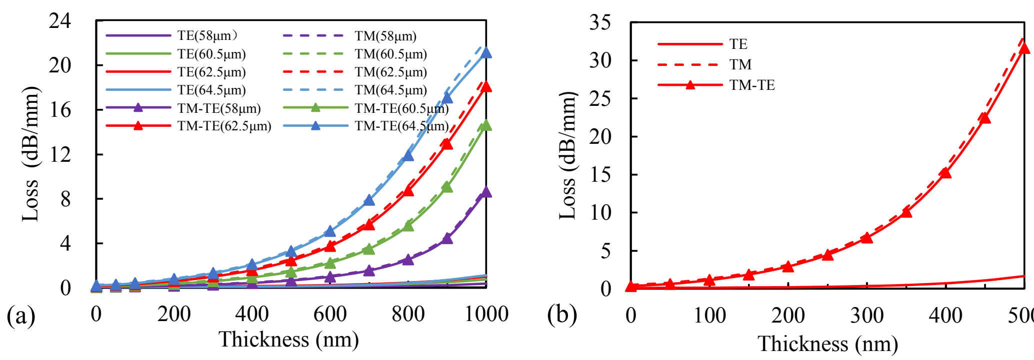

Fig. 3. Dependence of the confinement losses of TE and TM modes on (a) the thickness of PMMA and the polishing depth for single stack DF polarizer, and on (b) the thickness of PMMA for double stack DF polarizer (d = 62.5 μm).

3. Sample fabrication and characterization

Figure 4(a) illustrates a schematic of a DF polarizer covered by a graphene/PMMA double stack, which can be integrated into in-line fiber network. The polarizer angle θ is defined as the angle between the polarizer direction of the linearly polarized light and the polished plane of the fiber. When the polarizer angle θ is 0° or 180°, the transmission mode is a TE mode, while TM mode occurs for θ = 90° or 270°. Figures 4(b) and 4(c) show microscope images of

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the polished DF surface and cross-section. The polished surface was obtained by the wheel side-polished method. The DF loss is dependent on the length and surface roughness of its side-polished facet. For a polishing depth is about 62.5 μm, the measured DF loss was smaller than 1 dB/mm and it can further be reduced by improving the roughness of the polished surface. The monolayer graphene was grown on copper foil by chemical vapor deposition (CVD). The Raman spectroscopy of the monolayer graphene used in the work is given in Fig. 4(d). A 400nm-thick PMMA film was uniformly spin-coated on the graphene sheet surface using a spin coater with a high rotation speed.

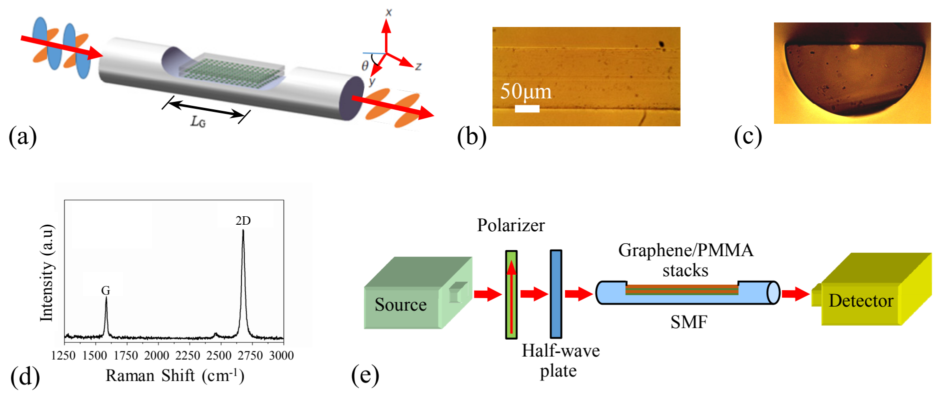

Fig. 4. (a) Schematic of the double graphene/PMMA stack DF polarizer. L_G is the propagation distance (length of graphene/PMMA stack). The polarizer angle θ is defined as the angle between the polarizer direction of the linearly polarized light and the polished plane of the fiber. (b)-(c) Optical micrograph of polished surface and cross-section of the DF. (d) Raman spectrum of the monolayer graphene. (e) Experimental setup for the extinction ratio measurement.

The copper foil was etched away by immersing it in ferric nitrate nonahydrate solution for 2 hours, while the remaining graphene-PMMA sheet was flushed in deionized water before being transferred onto the DF polished surface. The evaporation of any residual solvent improved the contact between the graphene sheet and the fiber surface, resulting in a single graphene/PMMA stack. The above-mentioned operation was repeated to transfer a second graphene/PMMA sheet, producing a DF polarizer covered by a double graphene/PMMA stack.

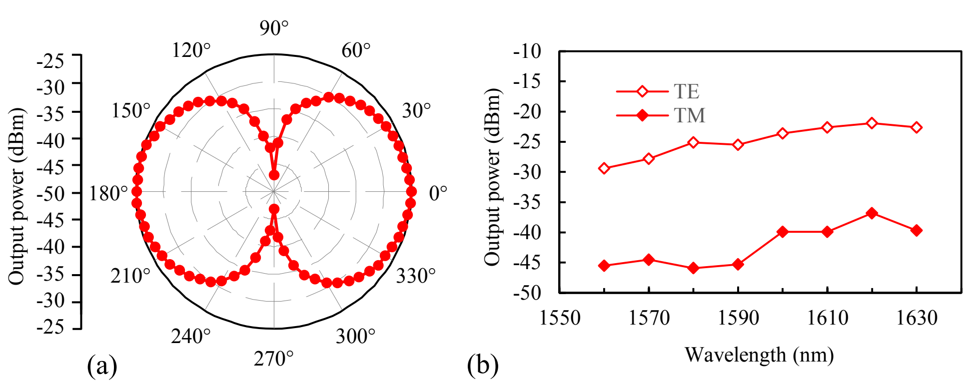

Fig. 5. (a) Polar image of the polarizer output power measured at $\lambda = 1580$ nm. (b) TE and TM modes polarization measurement in the wavelength range $\lambda = 1560$-1630 nm for a DF polarizer with single graphene/PMMA stack ($L_G = 6$ mm and $h_{PMMA} = 700$ nm).

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Figure 4(e) displays the experimental setup for the polarization measurement. A continuous wave (CW) tunable laser (λ = 1560-1630 nm, TSL-510) with output power of ~-15 dBm was chosen as the input light. A polarizer transformed the propagating light to a linearly polarized light and a half-wave plate was used to rotate the polarization direction of light, then the signal was injected into the SMF pigtail of the proposed in-fiber polarizer. The output power was then monitored by a power meter. By rotating the half-wave plate azimuth, the intensity of polarized light in different polarization directions could be obtained. The measured results for a polarizer sample with single graphene/PMMA stack are shown in Fig. 5, where the length L_G of the graphene/PMMA stack is 6 mm. The large length L_G introduces a large loss. The polar plot at 1580 nm in Fig. 5(a) shows that the output power at $\theta = 0°$ and 180° is −25.1 ± 0.3 dBm, while at $\theta = 90°$ and 270° rapidly reduces to −45.9 ± 0.5 dBm, providing a polarizer extinction ratio of 21 dB smaller than the theoretical value (30.5 dB) shown in Fig. 3(a). The discrepancy can be attributed to the non-uniform thickness of the PMMA film or wrinkle of graphene film introduced by the long device length. Figure 5(b) shows the polarization measurements performed in the wavelength range λ = 1560-1630 nm, indicating that the polarizer exhibits an extinction ratio of 21 ± 1.5 dB in a wide wavelength range. The insertion loss of the entire device is about ~10 dB at λ = 1580 nm, including 6 dB loss introduced by single graphene/PMMA stack and ~4 dB loss introduced by side polishing process, which is large for practice applications and yet smaller than that of previously reported polarizers [16].

In order to achieve higher extinction ratio and reduce insertion loss, a double graphene/PMMA stack structure was fabricated. The fiber was polished along a length of only 2.5 mm and the extinction ratio was measured in succession when the DF was covered by the first and second graphene/PMMA stack, respectively. The polar plot at λ = 1590 nm is illustrated in Fig. 6(a). The maximum output powers are −19 ± 0.5 dBm for the first graphene/PMMA stack (blue line) and −20 ± 0.5 dBm for the second graphene/PMMA stack (red line) at $\theta = 0°$ or 180°, respectively. Correspondingly, the minimum output powers are −23 ± 0.3 dBm and −56 ± 0.5 dBm at $\theta = 90°$ or 270°, respectively. The polarization characteristics are shown as a function of the wavelength in Fig. 6(b). While the extinction ratio was only 3.5 ± 0.5 dBm when the first graphene/PMMA stack was deposited, once the second graphene/PMMA stack was completed, the extinction ratio reached a maximum of ~36 dB at 1590 nm and was always better than 25 dB in the wavelength range λ = 1560-1630 nm. The fluctuation of the extinction ratio may result from the instability of the laser power. The measured value of 36 dB agrees well with the theoretical value of 40 dB (2.5 mm × 16 dB/mm) reported in Fig. 3. More importantly, the total loss is only 5 dB, including 3 dB loss introduced by the double graphene/PMMA stack and ~2 dB loss introduced by side polishing process. Therefore, the double graphene/PMMA stack coated DF can work as a TE-pass broadband polarizer with an extinction ratio of about 36 dB and low insertion loss as well as the compact size of only 2.5 mm.

A second sample of polarizer with a double graphene/PMMA stack with L_G = 4 mm was measured and the corresponding results are shown in Fig. 7. The extinction ratio was measured from λ = 1560 to λ = 1630 nm after the DF was coated by the second graphene/PMMA sheet. The maximum extinction ratio reached 44 dB at λ = 1620 nm, but the extinction ratio has a large fluctuation between the maximum value of 44 dB and the minimum value of 28 dB.

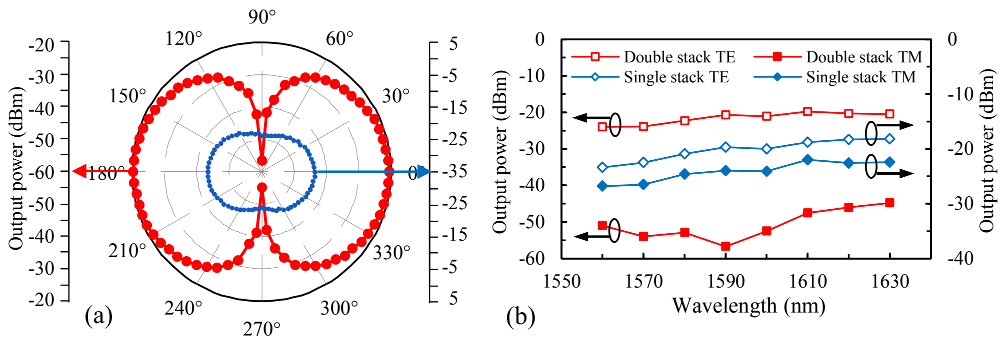

Fig. 6. (a) Polar image of the output power measured at λ = 1590 nm. The blue and red lines indicate the output powers for the first and second graphene/PMMA stack. (b) TE and TM modes polarization measurements for DF polarizers with single and double graphene/PMMA stack in the wavelength range λ = 1560-1630 nm (L_G = 2.5 mm and h_{PMMA} = 400 nm).

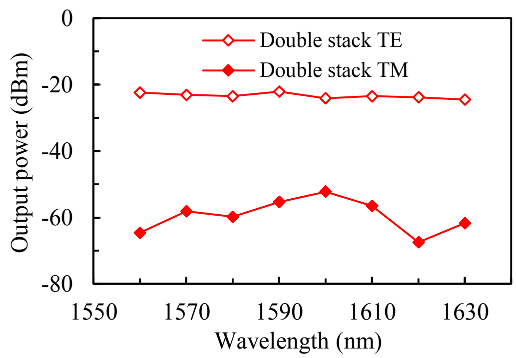

Fig. 7. Polarization measurement of TE and TM modes in the DF coated by a double graphene/PMMA stack with L_G = 4 mm.

For comparison, another structure, defined as no-stack, has also been studied. In this structure, a DF with L_G = 4 mm was coated by a graphene bilayer and then covered by a single PMMA sheet of h_{PMMA} = 700nm. The polar image of the output power in Fig. 8(a) shows a maximum extinction ratio of 28 dB at λ = 1620 nm. The extinction ratio fluctuates from 16 dBm to 28 dBm in the wavelength range λ = 1560-1630 nm as shown in Fig. 8(b). To obtain high extinction ratio, a polarizer with single graphene/PMMA stack or bilayer graphene/PMMA structure requires a long length L_G, which will hamper good film uniformity, thus the polarizer will suffer from the large insertion loss. Compared with all above discussed, the DF coated by graphene/PMMA stacks has great potential for in-fiber polarizer applications.

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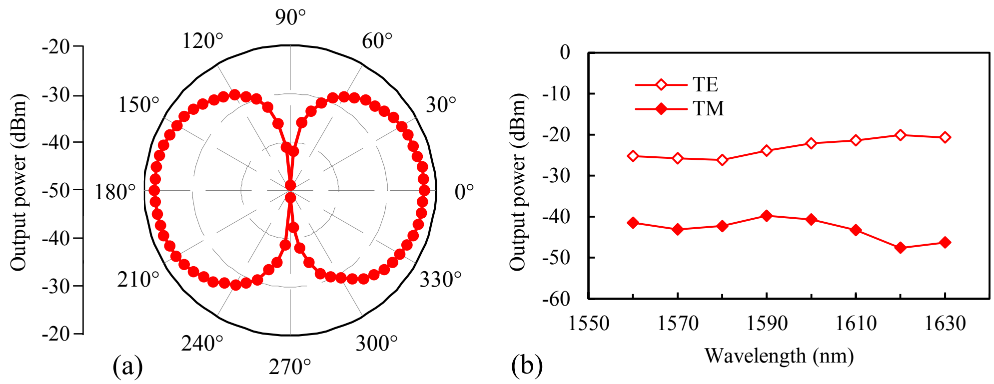

Fig. 8. (a) Polar image of the output power measured at λ = 1580 nm (L_G = 4 mm). (b) TE and TM modes polarization experiment of DF coated by a graphene bilayer and PMMA in the wavelength range λ = 1560-1630 nm.

4 Conclusion

In conclusion, a compact DF TE-pass polarizer coated with a double graphene/PMMA stack has been proposed. The polarizer had a high extinction ratio of ~36 dB, a low insertion loss of ~5 dB, and a small size of ~2.5mm. The insertion loss can further be reduced by improving the roughness of the polished surface. The extinction ratio reached a maximum of ~36 dB at 1590 nm and was always better than 25 dB in the wavelength range 1560-1630 nm. Furthermore, a polarizer with an extinction ratio of ~44 dB has also been achieved when the stack length was increased to 4 mm: to the best of our knowledge such a high extinction ratio has never been reported before. The proposed DF polarizer based on a double graphene/PMMA stack is compact, low-cost and capable of easy integration into conventional in-fiber system. It has smaller footprint and better performance than previously proposed polarizers that use graphene only for polarization selection. Moreover, the graphene/PMMA stack structure can be applied to manipulate the polarization state of light in other types of waveguides.

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