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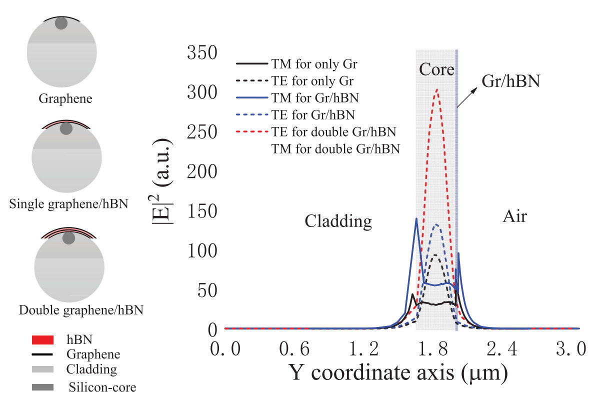

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In-Fiber Graphene-hBN Polarizer With Enhanced Performance and Bandwidth

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Abstract: Graphene and hBN as two-dimensional materials with excellent optical properties can be combined with other materials. In this paper, graphene and hBN is sequentially deposited on the surface of the silicon-core fiber to serve as transverse magnetic (TM) or transverse electric (TE) mode polarizer alternatively depending on the input wavelength and the diameter of the silicon-core. The Gr/hBN stack structure on the surface silicon-core microfiber is used not only for enlarging the wavelength bandwidth, such as from 350 nm (TM) and 670 nm (TE) for double Gr/hBN stack to 300 nm (TM) and 550 nm (TE) for single Gr/hBN stack, but also enhancing the light-graphene interaction to multiply the polarization extinction ratio, as compared with that of monolayer graphene. Small radius silicon core could provide large light-graphene interaction for flat extinction ratio with different thickness of the hBN.

Index Terms: In-fiber polarizer, silicon-core fiber, graphene, hBN, bandwidth.

1. Introduction

Optical polarizers are essential components in optic fiber communications, fiber sensing, 3D-imaging, etc. [1]–[4], for manipulating the polarization of electromagnetic (EM) waves in many systems. Conventional polarizers can be classified into three main operations: Brewster-angle reflected polarizer, sheet polarizer using anisotropic absorption media, prism polarizer by refraction [5]. These polarizers are expensive and have nonnegligible insertion losses, when used into fiber-optic systems or photonic circuits. The in-line fiber polarizer as a promising alternative can be compatibility with fiber-optic systems. The in-line fibre polarizer mainly relies on polarization-selective coupling between the evanescent field and birefringent crystal [6], liquid [7] or metal [8], graphene [9]–[16].

Compared to birefringent crystal, liquid, and metal, graphene as an ultra-thin material with many unique and remarkable physical properties including high carrier mobility, strong nonlinearity, ultrafast broadband response, can be easier to transfer on the fiber surface. In 2011, a broadband graphene fiber polarizer with extinction ratio of ∼27 dB and large insertion loss of ∼15 dB was demonstrated [9], which required monolayer graphene with graphene film length of 3.5 mm. Subsequently, D-typed surface core fiber polarizers [10] has been presented with a large attenuation difference between two orthogonal polarizations. For instance, graphene-based D-shaped fiber

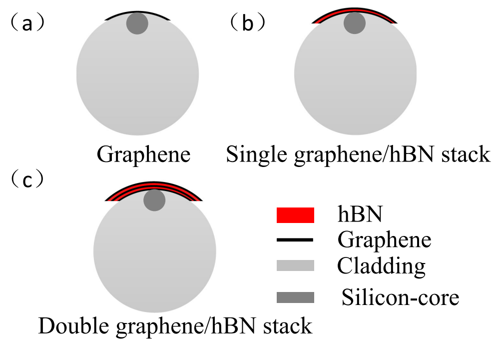

Fig. 1. The cross-section of the surface silicon-core microfiber with silica cladding coated by (a) monolayer graphene (Gr), (b) Gr/hBN/Gr (single Gr/hBN) stack, and (c) Gr/hBN/Gr/hBN/Gr (double Gr/hBN) stack on the surface silicon-core microfiber.

demoed over 41 dB TE/TM extinction ratio [11]. However, a long graphene film length over 4 mm is required, thus leading to a large inserted loss. In 2017, a double graphene/ PMMA stack was used on the surface of D-fiber to realize TE-pass polarizer with low inserted losses of 5 dB [12], by introducing PMMA to enhance the field distribution in the direction perpendicular to the graphene. However, these D-fibers or D-typed surface core fibers are required to have an ultra-smooth polished surface with a roughness of <1 nm RMS [13], which could increase the difficulty of device preparation and reduce the strength and durability.

Recently, silicon-core silica-cladding fibers [14] have attracted much interest, due to durability, their infrared transparency, strong evanescent field, high optical confining factor, and strong optical nonlinearities [15]. They provide many benefits such as robustness, ultra-smooth surface, and durability. Its evanescent field interacted with the graphene material could enable it to serve alternatively as a TM-pass or TE-pass polarizer depending on the diameter of the silicon-core [16], however it also needs a long graphene length over 1 mm to realize a large polarization extinction ratio.

In this paper, the graphene and hexagonal boron nitride (hBN) material is sequentially deposited on the surface silicon-core silica-cladding microfiber for realizing a graphene-fiber polarizer with high extinction ratio and ultra-wide bandwidth. By introducing such structure, more energy is coupled into the graphene films to decrease the graphene length and enlarge the bandwidth.

2. Structure Design and Theory

2.1 Structure Design

Surface silicon-core microfibers present a unique opportunity to study the interaction of the light and two-dimensional material in a configuration, where surface silicon-core has a strong evanescent field to provide an unbroken path of the propagating light. Fig. 1 shows the cross-section schematic of the graphene-fiber polarizers based on this microfiber, where monolayer graphene and hBN are sequentially deposited on the surface of the microfiber. Here, hBN as an insulator has a lattice constant similar to graphene [17], [18], and it also has an atomically smooth surface that is relatively free of dangling bonds and charge traps [18]. Thus, hBN is suitable for the insulator between the graphene film. Fig. 1(a) is the sectional view of a monolayer graphene on the surface silicon-core microfiber, Fig. 1(b) is the sectional view of a single monolayer graphene /hBN/ monolayer graphene (single Gr/hBN) stack on the surface silicon-core microfiber, and Fig. 1(c) is the sectional view of the monolayer graphene /hBN/ monolayer graphene /hBN/ monolayer graphene (double Gr/hBN) stack on the surface silicon-core microfiber. The multiple-layer structure would be fabricated by the PMMA-supported transfer method. Firstly, the monolayer graphene film on Cu substrate was spin-coated with the polymethylmethacrylate (PMMA) in chlorobenzene, and then Cu substrate was etched away by 1 mol/L $FeCl_3$ solution. The PMMA-supported graphene was washed with de-ionized water and then transferred on the microfiber surface. The hBN film like graphene can be utilized the same way to transfer on the microfiber surface.

2.1 Theoretical Analysis

Our proposed structure model consists of air, graphene, hBN, silicon core and silica cladding layers. A tightly strong evanescent field can be achieved by its small surface silicon core. Here, we use the finite element method (FEM) to solve Maxwell's equations in such model. The Maxwell's equation of our proposed model with graphene can be expressed as:

$$\nabla \times (\nabla \times E) = \omega^2 \mu_0 \varepsilon_r \varepsilon_0 E + j\omega\mu_0\sigma E \tag{1}$$

The complex dynamic conductivity σ_g is expressed by Kubo formalisms, including interband and intraband contributions [19]. The optical absorption of the graphene arises from the material's intraband and interband transitions, which is related with the chemical potential [9]. As we all known, monolayer graphene is modeled as a transition boundary condition with complex dynamic conductivity, so that the interband transition dominates the optical absorption. Graphene is an optically uni-axial anisotropic material of its 2D nature, so its permittivity tensor can be given by:

$$\varepsilon_g = \begin{bmatrix} \varepsilon_{g,t} & 0 & 0 \\ 0 & \varepsilon_{g,n} & 0 \\ 0 & 0 & \varepsilon_{g,t} \end{bmatrix} \tag{2}$$

The tangential permittivity of graphene is expressed as,

$$\varepsilon_{g,t} = 1 + j\frac{\sigma(\omega, \mu_c, \tau, T)}{\omega\varepsilon_0 t_g} \tag{3}$$

Here, ε_0 is the free space permittivity and t_g is the thickness of graphene. The normal component of the permittivity of graphene $\varepsilon_{g,n}$ should be 2.5. Its chemical potential μ_c is set to 0.04 eV. hBN like graphene is uni-axial anisotropic material, so the refractive index of hBN at infrared band can be set as $n_x = n_y = 1.98$, and $n_z = 1.72$ [20].

For simplicity, we used TE-polarized and TM-polarized modes to express the *x* and *y*-polarization of HE_{11} modes. In order to analyze the effect of the Gr/hBN stack, the FEM is utilized to discuss how the graphene and hBN material can modulate the polarized light in the silicon-core microfiber. Fig.2 shows the electromagnetic field distribution of TE and TM polarized light at 1550 nm in surface silicon-core (core dimeter of 170 nm) microfibers with a graphene monolayer, a single graphene/hBN stack and a double graphene/hBN stack. From Fig. 2, the maximal electronical field energy of the TE mode is about double of the TM mode. Compared to the inserted pictures in Fig. 2(b), (d) and (f), more electronical field energy of the TM polarizer light in the microfiber with the surface silicon-core of 170 nm couples into graphene and hBN film. The thin Gr/hBN stack could affect the mode field distribution of the surface core to move the energy closer to the graphene and hBN, further leading to the enhancement of the graphene and TM polarization-light interaction.

In order to explore deeply the reason why the Gr/hBN stack could enhance the interaction of graphene and polarization-light, the intensity of the electric field at y-axis ($x = 0$) has been extracted from Fig. 2, as shown in Fig. 3. The TE mode is described with the dashed line, and the TM mode is presented by the solid line. It is obviously shown that the TE mode has large power to propagate in the silicon core, while the TM mode has a large part of optical energy for coupling into the Gr/hBN film to enhance the optical absorption. More TE mode intensities of electric field are concentrated in the silicon core than that of the TM mode. Thus, at 170 nm silicon-core, a TE-passed polarizer has been realized. With the increase of the Gr/hBN layer, the electric field intensity of TE mode in the core is increased, as shown in Fig. 3. The optical power of TE mode in the silicon core with double Gr/hBN stack is double to that of the device with the single Gr/hBN stack. That means the Gr/hBN stack could enhance the graphene and polarization-light interaction for improving extinction ratio between TE and TM modes.

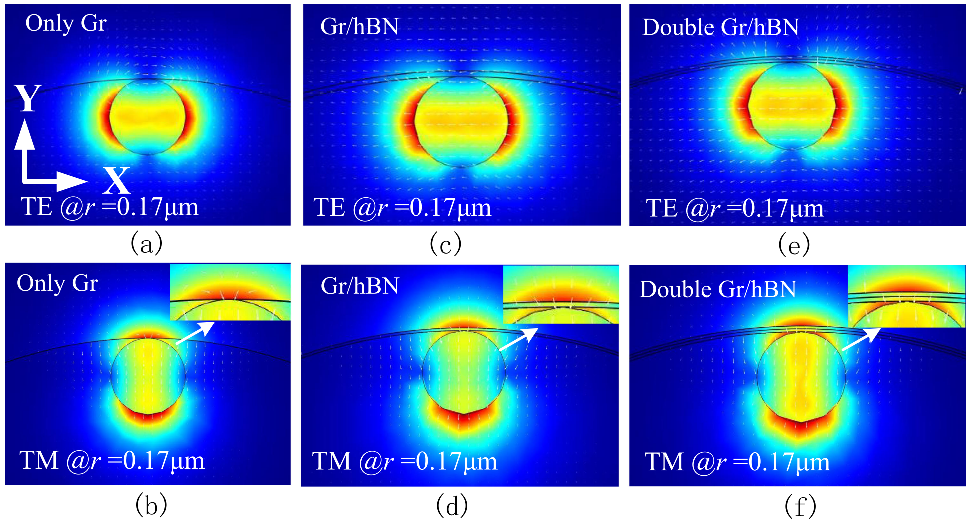

Fig. 2. The electric field distributions of TE/TM modes of TE polarizer at 1550 nm under the silicon-core radius $r = 170$ nm, which is (a) and (b) the surface silicon-core microfiber with monolayer graphene; (c) and (d) a single graphene/hBN stack on the surface silicon-core microfiber with monolayer graphene; (e) and (f) the double Gr/hBN stack on the surface silicon-core microfiber with monolayer graphene. At silicon-core radius of 170 nm, the polarizer with TE mode has larger electronical filed energy in the microfiber than that of TM mode. Thus, such polarizer is TM-passed. The thickness of dialectical layer hBN is 10 nm.

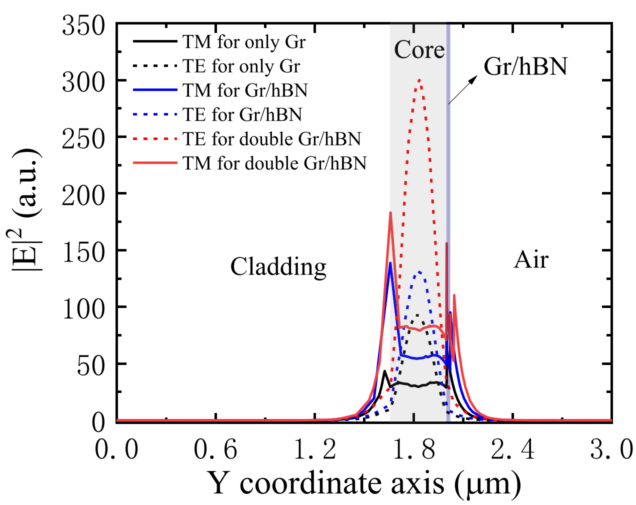

Fig. 3. The intensity of the electric field at 1550 nm as a function of y coordinate axis along x = 0 at the silicon core radius of 170 nm. More intensity of electric filed of TE mode is in the core than that of TM mode. The light gray in the silicon-core, and the light blue in the graphene.

3. Results and Discussion

The polarization mechanism is attributed to the differential attenuation constants of two orthogonal polarizations of the fundamental mode HE_{11}. The birefringence and attenuation constant are respectively calculated by the real part and image part of the effective refractive index of polarized modes. The polarization extinction ratio, which is the key factor to evaluate its performance, can be defined as [10]:

$$E_{(\alpha_{TE}-\alpha_{TM})} = 8.6858896 * k_0 * (\mathrm{Im}(n_{TE}) - \mathrm{Im}(n_{TM})) \quad (4)$$

where k_0 is the propagation constant of the light in the fiber.

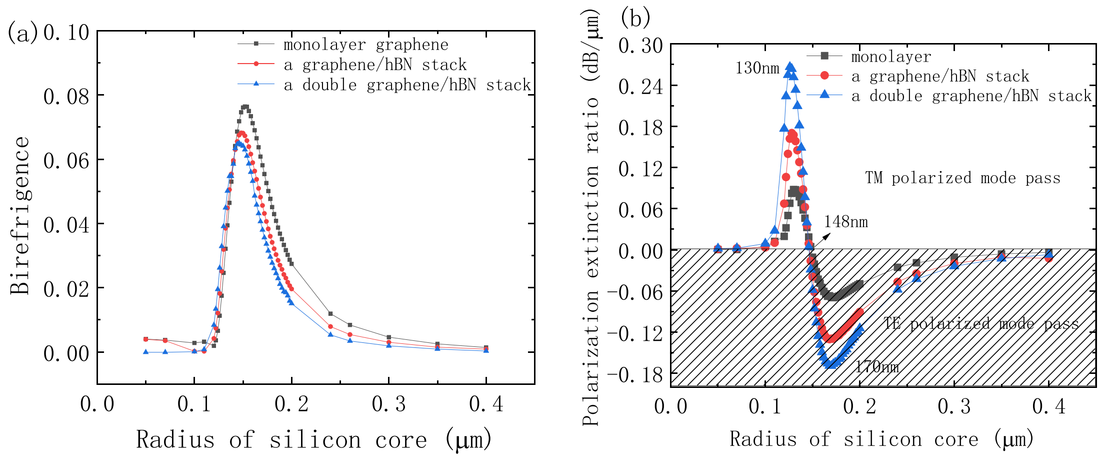

Fig. 4. (a) Birefringence and (b) polarization extinction ratio of the polarizer as a function of the radius of the surface silicon-core with Gr/hBN covered on silicon-core microfiber with graphene (hBN = 10 nm). Polarization-switched polarizer has been obtained by changing the radius of the silicon-core to tune the TM polarization to TE polarization.

Fig. 4(a) and (b) show the birefringence and polarization extinction ratio versus the silicon-core radius, respectively. When the silicon-core radius is about 151 nm, in Fig. 4(a), the surface silicon-core microfiber with the monolayer graphene has a maximal birefringence of 0.08, which is larger than that of the single Gr/hBN stack and the double Gr/hBN stack. Furthermore, its ultra-low polarization extinction ratio is of ~0.01 dB/μm. Thus, such microfiber with monolayer graphene at the core radius of ~151 nm is extremely suitable for polarization controlling in optical communications. From Fig. 4(b), the TE mode losses is larger than that of TM modes at the radius of the silicon core low to ~148 nm, while the TM mode suffers a larger loss than that of TE mode under the silicon core radius over ~148 nm. The mechanisms of its polarization come from broken symmetry of the device due to the surface-silicon-core with graphene/hBN, which makes the graphene have the difference absorption losses between TE and TM modes. Thus, the electrical distribution of two orthogonal polarization modes is determined by the silicon-core size. At the silicon-core radius of ~130 nm, high extinction ratio TM polarizers have been obtained with the double graphene/hBN (Gr/hBN) stack of ~0.25 dB/μm, the single Gr/hBN stack of ~0.17 dB/μm, and monolayer graphene of ~0.08 dB/μm. When the silicon-core radius is up to 170 nm, TE polarizers with the single Gr/hBN stack, the double Gr/hBN stack and monolayer graphene have been obtained with high extinction ratio of ~0.13 dB/μm, ~0.169 dB/μm, and ~0.069 dB/μm, respectively. The core size is lower than the wavelength of the light, and thus the silicon-core size has a large influence on the intensity distribution of the TE and TM modes. Therefore, the silicon-core size could control the polarization of the devices. Under the core-radius of 130 and 170 nm, the extinction ratios of the polarizer with the double Gr/hBN stack and the single Gr/hBN stack is nearly tripled or doubled as compared with that of monolayer graphene. The stack number increase of the Gr/hBN could multiply the polarization extinction ratio. According to Fig. 4, It is further verified that the increase of the Gr/hBN stack enhanced the polarized light and graphene interaction for the improvement of the polarization extinction ratio.

In order to further explore the impact of the Gr/hBN stack with different thickness of the hBN, the birefringence and polarization extinction ratios of the polarizer at silicon-core radius of 130 or 170 nm have been analyzed and discussed, as shown in Fig. 5. In Fig. 5(a), with the increase of the hBN thickness, the birefringence of the TM polarizer is increasing, and birefringence of the TE polarizer is decreasing. This is because the refractive index of the polarizer is mainly affected by the hBN thickness and the surface core size. The thickness of hBN has different effect on the extinction ratio of TE or TM polarizer. As shown in Fig. 5(b), the maximal extinction ratio of TM polarizer is located at the hBN thickness of 3 nm, by using whether the single or the double Gr/hBN stack.

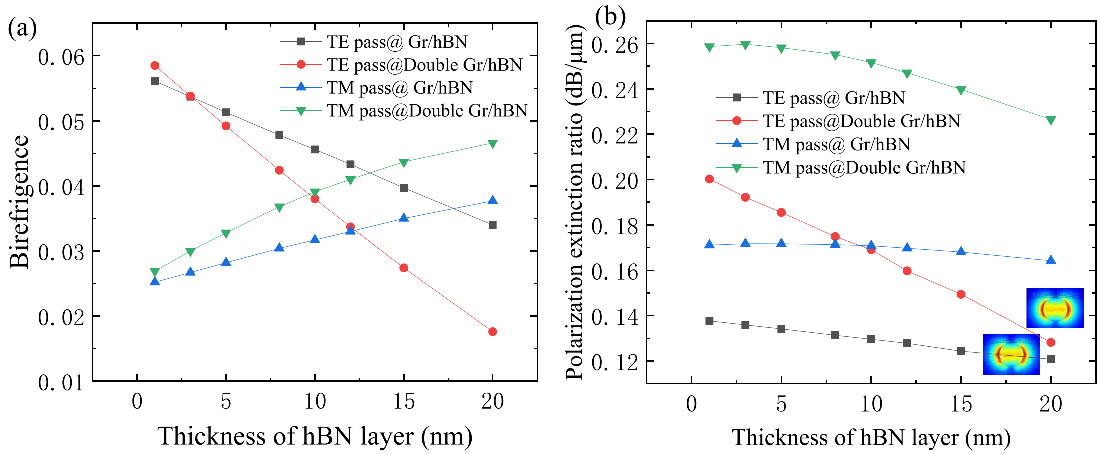

Fig. 5. Effect of the thickness of dielectric layer on (a) the birefringence and (b) the polarization extinction ratio to analyze the enhanced effect of Gr/hBN on the TE/TM polarizer.

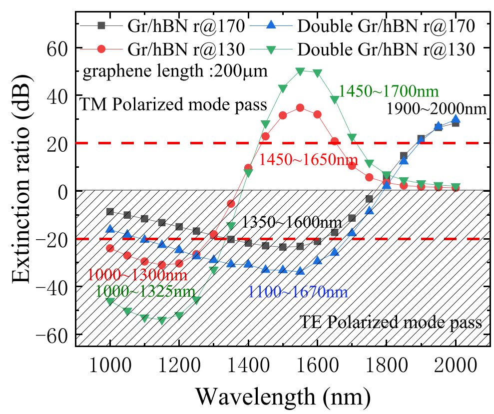

Fig. 6. Extinction ratio of the TE/TM polarizer versus the wavelength at silicon-core radius *r* of 130 and 170 nm and the length of graphene and dialectical layer of 200 μm.

Nevertheless, the smallest thickness of hBN about 1 nm could realize the largest extinction ratio of TE polarizer. Moreover, the influence of the hBN thickness on the TM/TE polarizer with the double Gr/hBN stack is larger than that of the single Gr/hBN stack. The large silicon core (170 nm) and the large thickness hBN (20 nm) could cause the small interaction between the outmost graphene film and tightly evanescent filed of the silicon-core, and thus the extinction ratio of the TE polarizer with double Gr/hBN stack is close to that of the single Gr/hBN stack, as shown in the inserted picture of Fig. 5(b). At the silicon core radius of 130 nm, the large optical evanescent filed of small core size cause that the extinction ratio of the TM polarizer is just slightly affected by the change of the hBN thickness. Thus, the TM polarizer has a flat extinction ratio with the change of the hBN thickness.

Neglecting the effect of the wavelength on the refractive index of graphene and hBN, the polarization extinction ratio of the polarizer with the Gr/hBN length of 200 μm has been calculated as a function of the wavelength, as shown in Fig. 6. It is found that the polarization characteristic is not only related with the silicon-core radius, but also switched by input light wavelengths. At the silicon-core radius of 130 nm, the TM polarizer can be changed to TE polarizer when the wavelength is low to 1350 nm. The TE polarizer with 170 nm-radius silicon-core can be tuned to TM polarizer, when the wavelength is large to 1800 nm. When the single Gr/hBN stack deposited on the surface silicon-core microfiber with 130 nm radius core, it achieves the TM polarizer with extinction ratio $>$20 dB at the wavelength range of 1450$\sim$1650 nm, and then tunes to the TE polarizer with extinction ratio >20 dB by decreasing the wavelength to 1300 nm. When the double Gr/hBN stack is used to replace the single Gr/hBN stack for keeping the extinction ratio >20 dB, the TM polarizer is also switched to the TE polarizer by tuning the wavelength from 1450∼1700 nm bandwidth to 1000∼1325 nm bandwidth. In a word, the extinction ratio of the polarizer with the double Gr/hBN stack is almost 1.5 times larger than that of the single Gr/hBN stack. The TE polarizer with the silicon-core radius of 170 nm and high extinction ratio up to ∼20 dB can be obtained with wavelength bandwidths of 1350∼1600 nm for single Gr/hBN stack and 1100∼1670 nm for double Gr/hBN stack, and then by tuning the wavelength up to 1900 nm they both switch to TM polarizer with extinction ratio over ∼20 dB. Under the extinction ratio over 20 dB, the polarization bandwidth of the polarizer with single Gr/hBN stack is about 300 nm (1450∼1650 nm and 1900∼2000 nm) for the TM and 550 nm (1350∼1600 nm and 1000∼1300 nm) for the TE. By utilizing double Gr/hBN stack, the polarization bandwidths of the polarizer with the extinction ratio > 20 dB are about 350 nm (1450∼1700 nm and 1900∼2000 nm) for TM and 670 nm (1100∼1670 nm and 1000∼1325 nm) for TE. Thus, the number increase of the Gr/hBN stack could increase the polarization bandwidths of such polarizer with 20 dB extinction ratio.

4. Conclusions

Graphene-fiber polarizers based on the Gr/hBN stack had been proposed and numerically analyzed in detail. The 151 nm-radius surface silicon-core microfiber with monolayer graphene is extremely suitable for polarization controlling application in optical communications, due to its maximal birefringence of 0.08. The maximal extinction ratios of TM and TE polarizers have been obtained at the silicon-core radius of 130 nm and 170 nm, respectively. The extinction ratios of such TM/TE polarizer with the double graphene/hBN (Gr/hBN) stack (∼0.25 dB/μm and ∼0.169 dB/μm) and the single Gr/hBN stack (∼0.17 dB/μm and ∼0.13 dB/μm) is nearly tripled or doubled as compared with that of monolayer graphene (∼0.08 dB/μm and ∼0.069 dB/μm). In addition, the thickness of the hBN could affect the birefringence and polarization extinction ratio of the TM/TE polarizer. The thick hBN and the large-radius silicon core could decrease the light-graphene interaction. The small radius silicon core could provide large light-graphene interaction for flat extinction ratio, with the change of the hBN thickness. The polarization characteristic is not only related with the silicon-core radius, but also switched by input light wavelengths. Moreover, its polarization bandwidth is related with stack number of the Gr/hBN. When the extinction ratio of the polarizer with 200 μm length is high to 20 dB, the polarizer with the single Gr/hBN stack has wide polarization bandwidth of 300 nm for TM and 550 nm for TE, and it with the double Gr/hBN stack has ultra-wide polarization bandwidth of 350 nm for TM and 670 nm for TE.

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