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Terahertz magneto-optical isolator based on graphene-silicon waveguide

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Dear editor,

Optical isolators and circulators are non-reciprocal one-way transmission devices, which only allow light to transmit in one direction and prevent light from transmitting in the opposite direction. Thus, they can protect the light source and detector in the integrated microwave or optical system, and also significantly reduce the additional noises. However, due to the limitation of material and device mechanism, the reported terahertz (THz) magneto-optical isolator and circulator are very rare, and most of them are free space discrete devices rather than integrated waveguide devices. For example, a THz Faraday rotation isolator based on the permanent magnet was demonstrated by Shalaby et al. in 2012 [1], but it is bulk and has strong insertion loss.

Graphene is a two-dimensional Dirac semiconductor, of which optical properties can be feasibly controlled by the external fields [2]. Moreover, graphene exhibits significant THz Faraday rotation and circular dichroism in an external magnetic field. The detailed theoretical analysis of graphene can be seen in Appendix A. For example, a graphene THz non-reciprocal isolator was experimentally demonstrated by Tamagnone et al. [3], which exhibits almost 20 dB of isolation and only 7.5 dB of insertion loss at 2.9 THz. Dmitriev et al. [4] proposed several THz magneto-optical circulators based on graphene, but most of the THz isolators were still designed in free space, and there are few THz isolators based on waveguide structure. Therefore, it is necessary to make more research in the THz waveguide isolator and circulator fields. In this study, the active isolators based on asymmetric graphene-silicon (Si) waveguide have been introduced in the THz regime. The magneto-optical effect of graphene and the asymmetry of waveguide structure together lead to time-reversal symmetry breaking of the transmission system. Based on this non-reciprocal transmission mechanism of the graphene-Si waveguide, a resonant ring isolator is achieved with the isolation degree up to 45 dB.

As shown in Figure 1(a), the graphene layer is attached to one side of the waveguide structure, and B is along the x-direction and perpendicular to the graphene layer, so the waveguide structure is asymmetric. The substrate material is SiO_2, and the waveguide material is Si. The details of geometries and other conditions can be found in Appendix B. We used COMSOL Multiphysics to simulate the field distributions for the forward and backward transmission. In this waveguide, the fundamental modes are no longer the strict TE and TM modes, in fact, they are both hybrid polarization modes. The fundamental modes of the forward and backward transmission are shown in Figure 1(b). The electric field of the forward wave goes along the y-direction (longitudinal mode), and the backward goes along the x-direction (transverse mode). The eigenmode analysis above shows that this magneto-optical waveguide supports different orthogonal polarization modes in the forward and backward transmission, which is the theoretical basis for the realization of non-reciprocal transmission.

Next, the longitudinal polarized waves are excited along the y-axis at both forward and backward incident ports, and the detector also detects the longitudinal polarization component at the output port. When $B = 0$ T, both forward and backward waves that pass through the waveguide are the same because there is no nonreciprocal transmission effect. But when $B = 1.5$ T shown in Figure 1(c), the forward wave can be transmitted, but the backward wave is lower than the forward wave transmission in the range of 1.35–1.85 THz, especially there is almost no longitudinal polarization component output at 1.5 THz of only −30 dB. If the biased magnetic field is reversed, the forward and reverse transmission spectral curves will be exchanged. This shows that the waveguide realizes non-reciprocal one-way transmission. The isolation (Iso $= T_{2,1} - T_{1,2}$) of this one-way transmission reaches 30 dB at 1.5 T. As shown in Figure 1(d), with the increase of the biased magnetic field from 0.75 to 2 T,

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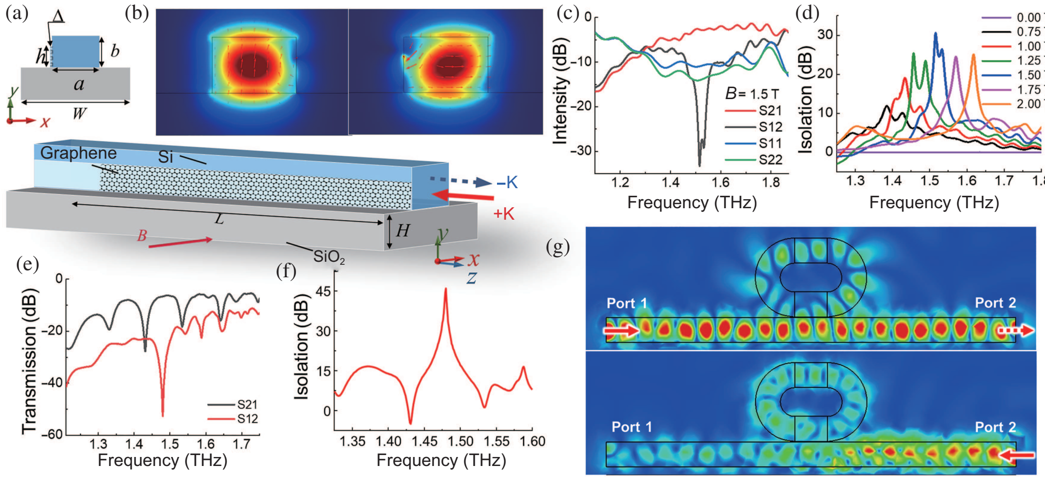

Figure 1 (Color online) (a) Geometry of the asymmetric graphene-Si waveguide structure. (b) Fundamental mode pattern of (c) forward (+K) and (d) backward transmission (−K). (c) Forward (S21) and backward (S12) transmission and reflection (S11 and S22) spectra of the graphene-Si waveguide at 1.5 T. (d) Isolation spectrum under different magnetic fields. (e) Forward transmission, backward transmission, and (f) isolation spectra of the resonant ring isolator when $B = 2$ T, $V = 60$ V, $T = 80$ K. (g) Electric field intensity distribution of the forward transmission (Port 1 → 2) and backward transmission (Port 2 → 1) when $f = 1.48$ THz, $B = 2$ T.

the isolation peak broadly moves from 1.4 to 1.65 THz. The operating frequency of the device can be controlled by the external magnetic field.

Then, by adding a resonance ring, the transmission valley of the backward transmission can be adjusted to the peak of the forward transmission. In this case, the isolation of the fundamental modes can be effectively increased by using the coupling of the graphene-Si waveguide structure and the Si resonant ring. The details of geometries can be found in Appendix C. Figure 1(e) shows the forward transmission spectrum of the resonant ring isolator. The isolation curve is shown in Figure 1(f), of which the maximum value is up to 45 dB, and the operating frequency range is approximately in the range of 1.34–1.42 THz and 1.44–1.52 THz, both the 10 dB-bandwidth is about 160 GHz. When $f = 1.48$ THz, $B = 2$ T, the electric field distribution of forward and reverse transmission is shown in Figure 1(g). As we can see, the light can transmit forward from Port 1 to Port 2, but cannot backward from Port 2 to Port 1. When the biased magnetic field is reversed, the THz wave can transmit backward, but cannot transmit forward.

The following is a brief analysis of the working mechanism of the device and the reason why the isolation is enhanced. When the light transmits forwards, the graphene layer has little impact on the fundamental longitudinal mode, so the transmission curve satisfies the resonance principle of the ring resonator. When light transmits in reverse from Port 2 to Port 1, due to the impact of graphene materials on the effective refractive index of eigenmode, the resonant frequencies changes, and there is an obvious resonance peak at $f = 1.48$ THz, so the isolation degree is effectively increased. Due to the addition of ring resonator which introduces coupling and bending loss, the isolation of resonant ring isolator structure to fundamental longitudinal mode becomes higher in the frequency range of 1.34–1.42 THz. In general, the isolation of resonant ring isolator increases to 45 dB, effectively improving the performances of the isolator.

On the basis of this ring waveguide, we also design a four-port ring isolator. When $B = 0.9$ T, the transmission cycle of the four-port isolator is Port 4 → 1 → 2 → 3 → ×. And when $B = -0.9$ T, the transmission cycle becomes reverse which is Port 3 → 2 → 1 → 4 → ×. Therefore, this device realizes nonreciprocal one-way transmission. The details can be seen in Appendix D.

In summary, the graphene-Si waveguide structure, which breaks the time-reversal symmetry and realizes nonreciprocal polarization conversion, has been proposed combining both the magneto-optical effect of graphene and the asymmetry of the waveguide structure. Based on the nonreciprocal polarization conversion, we have designed a resonant ring isolator with the maximum isolation degree up to 45 dB and the insertion loss of 5 dB, whose working frequency band of resonant ring isolator can be controlled by both external bias magnetic field and voltage. THz nonreciprocal one-way transmission in the waveguide structure is strongly determined by the relationship with structural asymmetry, the polarization direction of the THz electric field, and the direction of the biased magnetic field. The actively tunable magneto-optical Si waveguide isolator with low loss and high isolation has a promising prospect in THz integrated chip systems.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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