Strong Nonreciprocal Radiation in an InAs Film by Critical Coupling with a Dielectric Grating

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Abstract

Magneto-optical materials, which can violate the traditional Kirchhoff's law, provide new opportunities in energy harvesting and infrared camouflage. However, bulk magneto-optical materials usually possess weak nonreciprocity in the infrared band, which heavily impedes their applications in thermal radiation. Therefore, it is urgent to propose new methods to realize strong nonreciprocity in an infrared bands with an external magnetic fields as small as possible. Herein, we propose to enhance the nonreciprocal radiation in an InAs film by critical coupling with a dielectric grating. The numerical results show that strong nonreciprocal radiation can be obtained at wavelength 15.835 μm when the external magnetic field is 2 Tesla. The enhanced nonreciprocity is attributed to the critical coupling between the intrinsic loss in the InAs film and the external leakage in the dielectric grating. Both coupled mode theory and distribution of magnetic field are used to confirm the underlying mechanism. We believe that the method proposed in this work is of practical interest.

Keywords: Nonreciprocal radiation; Critical coupling; Dielectric grating.

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1. Introduction

Traditional Kirchhoff's law relates the emissivity and absorptivity of any object, which plays a vital role in radiation heat transfer and is commonly recognized in Refs.^[1-3] However, recent studies suggested that magneto-optical materials, such as InAs, InSb, graphene, and type-I magnetic Weyl semimetal, could violate the traditional Kirchhoff's law.^[4-13] That is to say, the traditional Kirchhoff's law only holds for reciprocal materials, but not for nonreciprocal materials. Very recently, Zhang *et al.* generalized the traditional Kirchhoff's law for anisotropic materials by considering the polarization conversion between linearly polarized waves.^[14]

The phenomenon that spectral directional emissivity and absorptivity are not identical, is termed nonreciprocal radiation (NRR), which provides new opportunities in energy harvesting and infrared camouflage.^[10,15] The NRR can be realized with magneto-optical materials under an external magnetic field.^[4-6] Generally speaking, the bigger the magnetic field is, the stronger the NRR is. However, the small magnetic

field is preferable in practical applications. By exciting the guided resonances in InAs, Zhu and Fan proposed a grating structure to realize strong NRR at wavelength 15.96 μm when the external magnetic field is 3 T.^[4] Recently, Zhao *et al.* realized strong NRR in InAs when the external magnetic field is 0.3 T.^[5] However, the wavelength is as far as 24.92 μm . According to the dispersion of the permittivity of InAs, the magneto-optical effect of one InAs film becomes stronger with the increase of the wavelength, *i.e.*, strong NRR is easier to be realized at long wavelength.^[10] Therefore, the proposed structure in Ref.^[5] cannot guarantee strong NRR at shorter wavelengths. However, for thermal radiation, the temperature is usually larger than 300 K, and thus the wavelength of interest is usually smaller than 20 μm . Therefore, it is desirable to realize strong NRR at a wavelength as shorter as possible with a small external magnetic field.

In this work, by critical coupling with a dielectric grating, we show that the nonreciprocity of one InAs film can be significantly enhanced. Strong NRR can be realized at wavelength 15.835 μm when the external magnetic field is 2 T, which is smaller than that required in Ref.^[4] The coupled mode theory and distribution of magnetic field are used to verify the mechanism.

2. Modeling

As shown in Fig. 1, the proposed structure consists of one InAs

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film with thickness d_1 and one Si grating with thickness d_2 . The substrate is Ag with a thickness of $0.2 \mu\text{m}$, which is optically thick. The permittivity of Si is 12.1, and those of InAs and Ag can be obtained from Ref.^[10] The period and filling ratio of the grating are P and f , respectively. The role of the grating is to provide the external leakage ratio same as the intrinsic loss of the InAs slab, giving rise to the critical coupling.

We consider the transverse magnetic (TM) wave with electric fields in the x - y plane, thus there is no polarization conversion between two linearly polarized waves. The absorptivity and emissivity can be obtained respectively by^[14]

$$\begin{aligned}\alpha(\theta) &= 1 - R(\theta) - T(\theta), \alpha(-\theta) \\ &= 1 - R(-\theta) - T(-\theta)\end{aligned}\quad (1)$$

and

$$\begin{aligned}\varepsilon(\theta) &= 1 - R(-\theta) - T(\theta), \varepsilon(-\theta) \\ &= 1 - R(\theta) - T(-\theta)\end{aligned}\quad (2)$$

where R and T are respectively the reflectivity and transmissivity, and θ and $-\theta$ are angles of incidence. The reflectivity and transmissivity can be calculated by the rigorous coupled-wave analysis (RCWA). The RCWA is a relatively straightforward technique for obtaining the exact solution of Maxwell's equations for electromagnetic diffraction by grating structures.^[16,17] In the grating regions, the electric and magnetic fields are expressed with a Fourier expansion. The RCWA algorithm for anisotropic materials has been described in detail in Ref.^[18] The inverse of the permittivity is used for the sake of speeding up and guaranteeing convergence according to the Fourier factorization rule.^[19,20] Our RCWA code was validated by the Fourier modal method,^[21] which has been adapted to calculate the optical properties of nonreciprocal structures in Ref.^[4] With the proper choice of the geometric parameters of Si grating and InAs film, the intrinsic loss rate in InAs film and the external leakage rate in dielectric grating can be the same,

resulting in perfect absorption and emission.^[22-24]

Fig. 1 A schematic of the proposed structure for strong nonreciprocal radiation. The structure consists of an InAs film and a Si grating atop a uniform Ag layer. The thicknesses of the InAs film and Si grating are d_1 and d_2 , respectively. The filling ratio and period of the grating are f and P , respectively. An external magnetic field is applied in the z -direction.

3. Results and discussion

After optimization, the geometric parameters of Si grating and InAs film are: $d_1 = 1.3 \mu\text{m}$, $d_2 = 0.2 \mu\text{m}$, $P = 7.24 \mu\text{m}$, and $f = 0.34$. When the angle of incidence is 54.75° , the absorptivity and emissivity spectra of the whole structure presented in Fig. 1 are shown in Fig. 2(a). One can see that the absorptivity equals the emissivity when there is no magnetic field. When the magnetic field is 2 T, the absorptivity blueshifts while the emissivity redshifts, resulting in strong NRR. At wavelength $15.835 \mu\text{m}$, the contrast ratio between the directional spectral emissivity and absorptivity is as large as 10.2 dB. Compared with Ref.^[4], the strong NRR can be achieved with a smaller magnetic field, which is preferable for practical applications. Besides, for comparison, the emissivity and absorptivity for a

Fig. 2 (a) The absorptivity and emissivity spectra at an angle of incidence of 54.75° : (a) the whole structure shown in Fig. 1; (b) the sole InAs film with a thickness of $1.3 \mu\text{m}$.

InAs film with a thickness of 1.3 μm is calculated, as shown in Fig. 2(b). One can see that both the emissivity and absorptivity are extremely smaller, never to mention their difference. By critical coupling with the dielectric grating, the emissivity and absorptivity of an InAs film are significantly enhanced, as well as the nonreciprocal radiation.

To verify the physical mechanism, the coupled mode theory (CMT) is used. The reflection coefficient of the whole structure can be described as^[24]

$$\Gamma = \frac{j(\omega - \omega_0) + \delta - \gamma}{j(\omega - \omega_0) + \delta + \gamma} \quad (3)$$

where ω_0 is the resonance angular frequency, and the absorptivity is^[24]

$$\alpha = 1 - |\Gamma|^2 = \frac{4\delta\gamma}{(\omega - \omega_0)^2 + (\delta + \gamma)^2} \quad (4)$$

From Eq. (4), the critical coupling condition can be achieved when the external leakage and intrinsic loss rates are the same, i.e., $\delta = \gamma$ at the resonant angular frequency ω_0 . Under this condition, the incident light will be absorbed. The intrinsic loss and external leakage rates can be obtained by fitting the theoretical and simulated curves, as shown in Fig. 3. Only the absorptivity spectrum under a magnetic field of 2 T is used to verify the critical coupling. The fitting values are $\delta = \gamma = 0.24$ THz at angular frequency ω_0 of 1.19×10^{14} rad/s (15.835 μm). The excellent fitting in the vicinity of the resonance validates the underlying mechanism. It should be noted that the CMT can also be used to verify the mechanism for emissivity. The results are not presented here since they are similar to those shown in Fig. 3.

Fig. 3 Simulated and theoretical absorption spectra at an angle of incidence of 54.75° when the magnetic field is 2 T.

To further confirm the mechanism, the distribution of the absolute magnetic field along the z -axis is also plotted. Figs 4(a) and 4(b) show the results at wavelength 15.835 μm for angles of incidence of 54.75° and -54.75°, respectively. The magnitude of the incident magnetic field is set to unity. For the angle of incidence of 54.75°, the magnetic field is greatly enhanced in the Si grating and the InAs film due to the critical coupling, resulting in perfect absorption. In addition, the

strong field confinement in the Si grating confirms the excitation of guided resonance.^[25,26] In contrast, for the angle of incidence of -54.75°, the magnetic field in the InAs is much weaker than that shown in Fig. 4(a), indicating that most of the incident power is reflected, resulting in a low absorptivity. Therefore, the physical mechanism is deeply revealed by the magnetic field distribution.

Fig. 4 The distribution of the absolute of the magnetic field along the z -axis at wavelength 15.835 μm : (a) angle of incidence of 54.75°; (b) angle of incidence of -54.75°. The magnitude of the incident magnetic field is set to unity.

Fig. 5 The absorptivity spectrum varies with the loss of the grating at an angle of incidence of 54.75°. The magnetic field is 2 T.

In Ref.^[5] it is shown that the loss of the grating could have a great impact on the NRR. In this work, the loss of the grating on the absorptivity is shown in Fig. 5. The real part of the permittivity of Si is fixed at 12.1, while the imaginary part is modified to simulate different losses. The solid green line presents the absorptivity spectrum when the imaginary part of the permittivity of Si is zero. One can see that the absorptivity almost does not change when the imaginary part of the

permittivity of Si is 0.1. Besides, there is a small change when the imaginary part of the permittivity of Si is 0.5. Even when the imaginary part is 1, the absorptivity does not change too much. The numerical results suggest that the absorptivity spectrum is insensitive to the loss of the Si. We have checked that the emissivity spectrum is also insensitive to the loss of the Si. Therefore, strong NRR can be obtained when the dielectric has a modest imaginary part of the permittivity. It indicates that the grating can be made from other materials, which releases the restriction on the materials.

Fig. 6 The absorptivity and emissivity spectra at an angle of incidence of 54.75° varying with the thickness of the InAs film. The magnetic field is 2 T.

The absorptivity and emissivity spectra varying with the thickness of InAs are plotted in Fig. 6. Compared with results shown in Fig. 2(a), the peaks of absorptivity and emissivity redshift for the thickness of 1.2 μm, while this blueshift for the thickness of 1.4 μm. The modification of the thickness of the InAs film will influence the intrinsic loss of the InAs film, thereby resulting in the shift of wavelength for critical coupling. The absorptivity and emissivity peaks have big shifts varying with the thickness of InAs. Therefore, the thickness of the InAs can be used to tune the radiation properties.

Finally, the effects of the grating parameters on the absorptivity and emissivity are shown in Fig. 7. Comparing the results shown in Fig. 7(a) with Fig. 2(a), one can see that the peaks of absorptivity and emissivity shift to longer wavelength as the period of the grating increases. Besides, perfect absorptivity and emissivity can be obtained. From Fig. 7(b), one can see that the absorptivity and emissivity are not sensitive to the filling ratio of the grating, since the shifts of the peaks of absorptivity and emissivity are small by varying the filling ratio. As shown in Fig. 7(c), the absorptivity and emissivity are also not sensitive to the thickness of the grating. In addition, perfect absorptivity and emissivity cannot be obtained in this case. The reason is that the thickness of the grating has an impact on the external leakage rate of the grating, thereby influencing the critical coupling. Perfect

absorptivity and emissivity are possible to be achieved by modifying the intrinsic loss of the InAs film.

Fig. 7 The absorptivity and emissivity spectra varying with the grating parameters: (a) the period P ; (b) the filling ratio f , (c) the thickness d_2 .

4. Conclusions

In summary, we have proposed a nanophotonic design that can achieve strong nonreciprocal radiation at wavelength 15.835 μm with a magnetic field of 2 T, which is smaller than that required in Ref.^[4] The underlying mechanism is attributed to the critical coupling, which is confirmed by the coupled mode theory and distribution of the magnetic field. This work provides a new method to exploit nonreciprocal radiation.

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Conflict of interest

There are no conflicts to declare.

Supporting information

Not applicable

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