Broadband Nonreciprocal Thermal Emission

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Abstract

The reciprocity between thermal emission and absorption in materials that satisfy the Lorentz reciprocity places a fundamental constraint on photonic energy conversion and thermal management. For approaching the ultimate thermodynamic limits in various photonic energy conversion and achieving nonreciprocal radiative thermal management, broadband nonreciprocal thermal emission is desired. However, existing designs of nonreciprocal emitters are narrow-banded. Here, we introduce gradient epsilon-near-zero magneto-optical metamaterial for achieving broadband nonreciprocal thermal emission. We start by analyzing the nonreciprocal thermal emission and absorption in a thin layer of epsilon-near-zero magneto-optical material atop a substrate. We use temporal coupled mode theory to elucidate the mechanism of nonreciprocal emission in the thin film emitter. We then introduce a general approach for achieving broadband nonreciprocal emission by using a gradient epsilon-near-zero magneto-optical metamaterial. We numerically demonstrate broadband nonreciprocal emission in gradient-doped semiconductor multilayer, as well as in a magnetic Weyl semimetal multilayer with gradient chemical potential. Our approach for achieving broadband nonreciprocal emitters will be useful for developing broadband nonreciprocal devices for energy conversion and thermal management.

I. Introduction

Controlling thermal emission and absorption is important for applications [*1-4*] in energy conversion, thermal management, lighting, and imaging. Various photonic structures and materials have been used to control emission and absorption, such as metamaterials [*5, 6*], metasurfaces [*7, 8*], photonic crystals [*9-11*], multilayer [*12, 13*], epsilon-near-zero materials [*14, 15*], two-dimensional materials [*16, 17*], and phase-change materials [*18*], leading to applications such as thermophotovoltaics [*19-21*], solar cells [*22, 23*], and radiative cooling [*12, 24*]. However, the emission and absorption processes are typically constrained by a reciprocity relation. The Kirchhoff's law of thermal radiation [*25-27*] states that the emissivity equals the absorptivity at the same angle and frequency. Such reciprocity between emission and absorption places a stringent constraint on the performance of a range of applications such as solar cells [*28-30*], thermophotovoltaics [*31*], and harvesting outgoing radiation [*31, 32*].

Achieving nonreciprocal emission and absorption points to a fundamental pathway for improving a range of energy harvesting technologies, such as solar energy harvesting [*28-30*], thermophotovoltaics [*31*], harvesting energy from outgoing radiation [*31*], and simultaneously harvesting energy from the sun and the outer space [*32*]. Importantly, to achieve the ultimate thermodynamic limits in these applications [*28-32*], nonreciprocal emission and absorption all need be achieved over a broad band. A reciprocal solar cell needs emit luminescence towards the sun. Such luminescence cannot be used, and it represents energy loss. In contrast, a nonreciprocal solar cell can emit luminescence towards a direction away from the sun. Such luminescence can be collected using additional solar cells, leading to improvement of the overall efficiency. It has been pointed out that by using an array of nonreciprocal multijunction solar cells [*29*], or a nonreciprocal semitransparent multijunction solar cell [*30*], which achieve nonreciprocal emission

over all wavelengths, the efficiency can approach the Landsberg limit of 93.3%. Such efficiency is substantially higher than the limit of 86.8% in reciprocal systems. For thermophotovoltaics, the use of nonreciprocal emitters points to the possibility of achieving Carnot efficiency limit with maximum power output, which is impossible with reciprocal systems [*31*]. We also note that by using narrowband nonreciprocal emitters in thermophotovoltaics, it is possible to achieve Carnot efficiency limit, but with reduced power output. Further, broadband nonreciprocal emitters point to great potential for improving harvesting energy from outgoing thermal radiation. For harvesting thermal radiation from an ambient at 300 K to the outer space at 3 K, with nonreciprocal systems, the operating power density can approach a Landsberg limit [*31*] at 153.1 W m^{-2}, which greatly exceeds the limit of 55 W m^{-2} in reciprocal systems [*31*]. Also, broadband nonreciprocal emitters point to improving co-harvesting energy from the sun and the outer space [*32*].

Besides energy harvesting, achieving nonreciprocal emission and absorption points to nonreciprocal heat flux control [*33*] and communication [*34*]. For nonreciprocal heat flux control and communication, broadband nonreciprocal emitters are desirable for enhancing the magnitude of heat flux, and bandwidth of communication, respectively.

Nonreciprocal emission and absorption have been predicted in systems with magneto-optical materials [*35-38*], Kerr nonlinearity [*39*] or time-modulation [*40*]. Existing designs of nonreciprocal emitters typically rely on critical coupling in one resonance [*35-37*] or two resonances [*41, 42*]. Accordingly, strong nonreciprocal emission is achieved only near one or two resonances, leading to narrow bandwidth. To date, despite the importance of broadband nonreciprocal emission for energy harvesting, heat flux control, and communication, a general strategy for achieving broadband nonreciprocal emission is elusive.

In this article, we introduce a general approach for achieving broadband nonreciprocal emission by using gradient epsilon-near-zero magneto-optical metamaterial. We elucidate the mechanism of nonreciprocal emission in a thin film using a temporal coupled mode theory. We then numerically demonstrate broadband nonreciprocal emission in gradient doped semiconductors, and magnetic Weyl semimetals with gradient chemical potential. Our results can be useful for developing broadband nonreciprocal devices for energy conversion and thermal management.

II. Nonreciprocal emission in a single magneto-optical layer

We begin by considering emission and absorption in a thin film emitter shown in Fig. 1(a). The emitter consists of a magneto-optical film on top of a substrate. Without loss of generality, we consider 400 nm thick doped InSb film, and a substrate with relative permittivity $\epsilon_S = -2$. We consider TM polarization with emission angle θ. We first introduce the dielectric model of doped semiconductor. For doped semiconductor, in external magnetic field, due to free-carrier effect, the permittivity of the material is described by a nonsymmetric tensor [*43*]. With magnetic field along the *y* axis, the relative permittivity tensor of doped InSb is:

$$\overleftrightarrow{\epsilon} = \begin{bmatrix} \epsilon_\infty - \dfrac{{\omega_p}^2(\omega - i\Gamma)}{\omega[(\omega - i\Gamma)^2 - {\omega_c}^2]} & 0 & -\dfrac{i{\omega_p}^2\omega_c}{\omega[(\omega - i\Gamma)^2 - {\omega_c}^2]} \\ 0 & \epsilon_\infty - \dfrac{{\omega_p}^2}{\omega(\omega - i\Gamma)} & 0 \\ \dfrac{i{\omega_p}^2\omega_c}{\omega[(\omega - i\Gamma)^2 - {\omega_c}^2]} & 0 & \epsilon_\infty - \dfrac{{\omega_p}^2(\omega - i\Gamma)}{\omega[(\omega - i\Gamma)^2 - {\omega_c}^2]} \end{bmatrix},$$

where $\epsilon_\infty = 15.68$ is the high-frequency permittivity, $\omega_p = \sqrt{n_e e^2/(m^*\epsilon_0)}$ is the plasma frequency, Γ is the relaxation rate, and $\omega_c = eB/m^*$ is the cyclotron frequency. Here, n_e is the electron doping concentration, e is the charge for a proton, m^* is the effective electron mass, and ϵ_0 is the vacuum permittivity. We consider a doping concentration $n_e = 8 \times 10^{18}\ cm^{-3}$. At such

doping concentration, the electron mobility is $\mu_n = 6730\ cm^2\ V^{-1}\ s^{-1}$ [*44*], $m^* = 0.707\ m_e$ where m_e is the rest mass of the electron, and the relaxation rate $\Gamma = 3.658 \times 10^{12}\ rad\ s^{-1}$ from $\mu_n = e/(m^*\Gamma)$. The effective electron mass is calculated using a model [*45, 46*] considering the nonparabolicity of the conduction band $m^* = m_n\left[1 + \frac{1}{2}\left(\frac{3}{\pi}\right)^{\frac{2}{3}}\frac{h^2}{E_g m_n}n_e^{\frac{2}{3}}\right]^{1/2}$, where the bandgap energy is $E_g = 0.17\ eV$ at 300 K, $m_n = 0.014\ m_e$ is the electron effective mass at the bottom of the conduction band, and h is the Planck's constant.

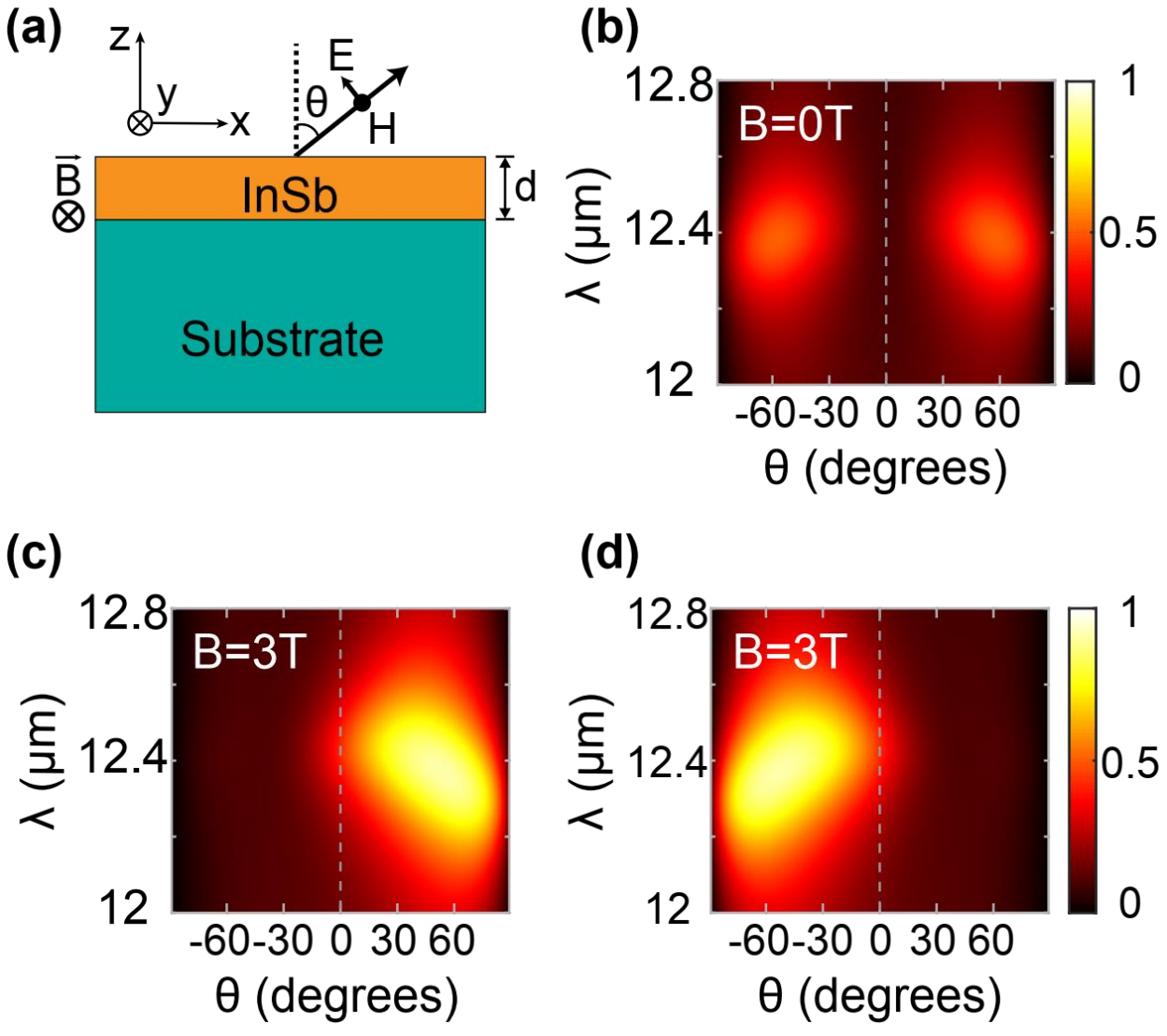

FIG. 1. Nonreciprocal emitter based on one layer of magneto-optical material. (a) Schematic of a doped InSb layer on top of a substrate. The InSb layer has a thickness of $400\ nm$, and is doped with electron concentration of $8 \times 10^{18}\ cm^{-3}$. The substrate has constant relative permittivity $\epsilon_S = -2$. (b) The calculated emissivity ε and absorptivity α of the structure in (a) as a function of wavelength and angle when there is no external magnetic field. Here, the emissivity and absorptivity are identical. (c) Calculated emissivity ε and (d) absorptivity α of the structure in (a) under a 3 T magnetic field. The emissivities in (b-c) are calculated using fluctuational electrodynamics.

We calculate the emissivity and absorptivity of the structure in Fig. 1(a) using fluctuational electrodynamics [*35, 47, 48*]. Without external magnetic field, the emissivity and absorptivity are reciprocal, i.e., $\varepsilon(\theta, \lambda) = \alpha(\theta, \lambda)$, as shown in Fig. 1(b). In such case, due to the mirror symmetry with respect to the *y*-*z* plane, the emissivity is symmetric with respect to angle θ, that is $\varepsilon(\theta, \lambda) = \varepsilon(-\theta, \lambda)$. The emission and absorption are due to Berreman mode [*14*] at wavelength about $12.4\ \mu m$, where the diagonal component of permittivity (ε_{xx}) of the magneto-optical layer is near zero (Fig. 3(b)).

With an external magnetic field applied along the *y* axis, the emissivity and absorptivity change in opposite trends, as shown in Fig. 1(c-d). With 3 T magnetic field, compared with the case without magnetic field, the emissivity is greatly enhanced at angle $\theta > 0$ (Fig. 1(c)), and the absorptivity is greatly suppressed at angle $\theta > 0$ (Fig. 1(d)). The enhancement of emissivity and the suppression of absorptivity at the same angle lead to strong breaking of the Kirchhoff's law of thermal radiation, i.e., $\epsilon(\theta, \lambda) \neq \alpha(\theta, \lambda)$. As an example, at angle $\theta = 60°$ and wavelength $\lambda = 12.35$ μm, the emissivity and absorptivity are 0.908 and 0.112, respectively.

III. Temporal coupled mode theory

We employ temporal coupled mode theory to elucidate the mechanism of the strong nonreciprocal emission [*49*]. We consider an emission mode at resonance frequency ω_r. From temporal coupled mode theory, the emissivity is

$$\varepsilon = \frac{4\gamma_i\gamma_e}{(\omega-\omega_r)^2+(\gamma_i+\gamma_e)^2}, \tag{1}$$

where ω is the angular frequency. For the emission mode, the total modal decay rate is the sum of an intrinsic decay rate γ_i due to material loss and an external decay rate γ_e due to radiation. For a nearly lossless version of the emission mode, that is, when the intrinsic decay rate is near zero, the external decay rate exclusively defines the total modal decay rate.

We solve the dispersion relation for the thin film emitter structure shown in Fig. 1(a), for both the lossy case, and the nearly lossless case with Γ set to zero. The dispersion relation $\omega(k_x)$ of the TM mode for the thin film structure [*50*] is given by:

$$i\tan(k_z d) = -\frac{\epsilon_{xx}k_z\left(k_{z,V}+\frac{k_{z,S}}{\epsilon_S}\right)}{\epsilon_{xx}k_0^2-k_x^2+k_x\epsilon_{xz}\left(k_{z,V}-\frac{k_{z,S}}{\epsilon_S}\right)+k_{z,V}\frac{k_{z,S}(\epsilon_{xx}^2+\epsilon_{xz}^2)}{\epsilon_S}}. \tag{2}$$

Here, k_x is the wavevector along x axis, $k_0 = \omega/c$ is the wavevector in vacuum where c is the velocity of light in vacuum, and $k_z = \sqrt{k_0^2\left(\epsilon_{xx}+\frac{\epsilon_{xz}^2}{\epsilon_{xx}}\right)-k_x^2}$, $k_{z,V} = \sqrt{k_0^2-k_x^2}$, and $k_{z,S} = \sqrt{\epsilon_S k_0^2-k_x^2}$ denote the z-component of wavevector in the magneto-optical layer, vacuum, and the substrate, respectively. As the mode has loss, we solve the dispersion relation with complex ω and real k_x [*14*]. The real part of the eigenfrequency represents the resonance frequency ω_r, and the imaginary part of the eigenfrequency represents the total modal loss rate. Thus, the imaginary part of the eigenfrequency in the lossy case is $(\gamma_i+\gamma_e)$, and the imaginary part of the eigenfrequency in the nearly lossless case is the external decay rate γ_e, from which the intrinsic decay rate γ_i can be obtained as the difference between the two.

Figure 2(a) shows the dispersion relation of the thin film emitter at varying magnetic fields. When there is no external magnetic field, the dispersion relation is symmetric with respect to angle

θ. In contrast, with external magnetic field, the dispersion relation becomes asymmetric with respect to θ and thus k_x. This can be understood from the fact that with external magnetic field, Eq. 2 has dependence on k_x in the first order via $k_x\epsilon_{xz}\left(k_{z,V}-\frac{k_{z,S}}{\epsilon_S}\right)$. The intrinsic decay rate as shown in Fig. 2(b) shows negligible dependence on the magnetic field and angle. The intrinsic decay rate is about $\Gamma/2$, which is consistent with fact that $\Gamma/2$ is the upper bound for intrinsic decay rate [*51*] due to material loss.

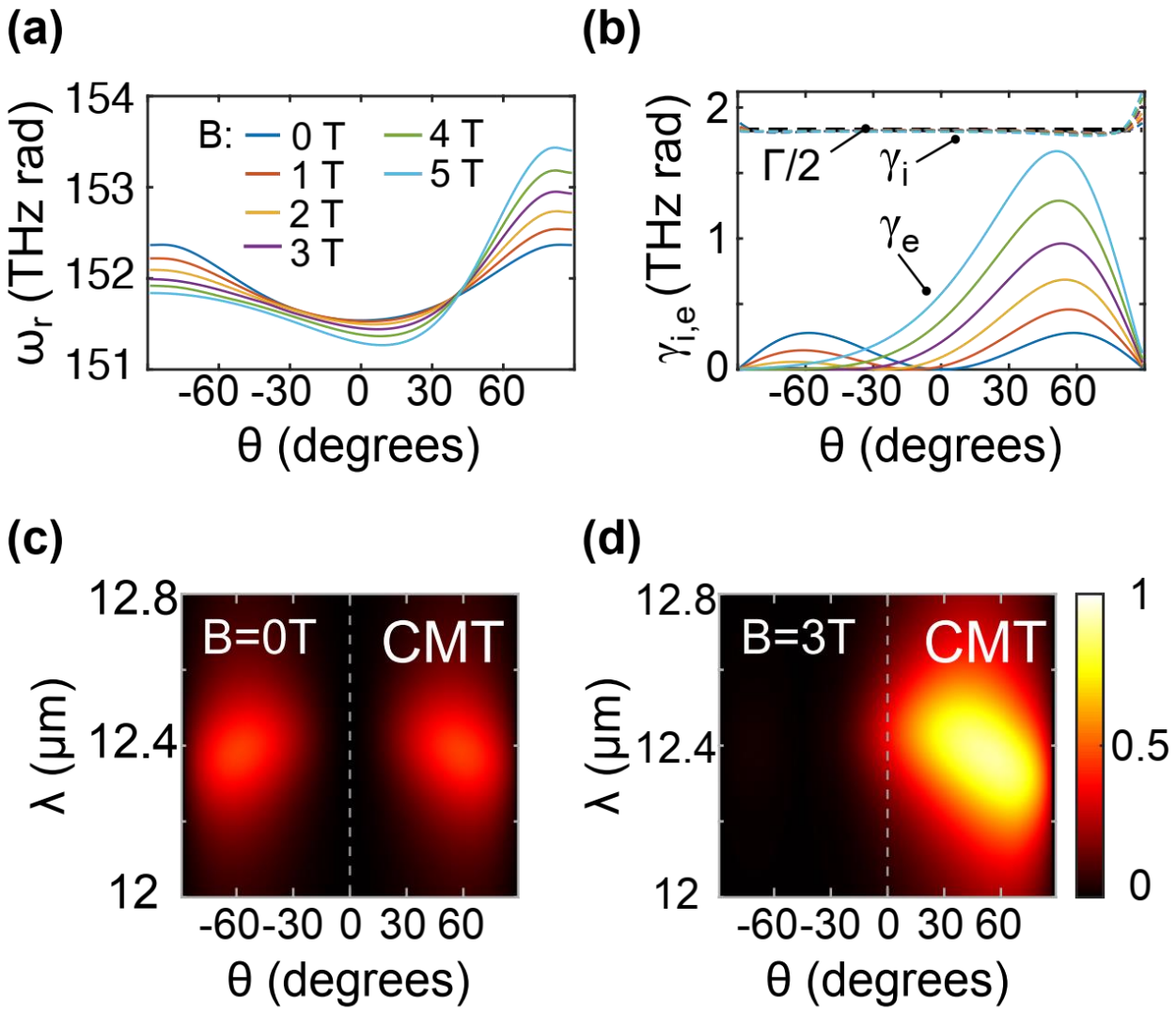

FIG. 2. Mechanism of nonreciprocal emission and absorption in one magneto-optical layer atop substrate. (a) Resonance frequency for the emission mode of the structure in Fig. 1(a) at varying angles θ and external magnetic fields B. (b) The intrinsic decay rate (dashed lines) and external decay rate (solid lines) of the emitter at varying angles and magnetic fields. (a) and (b) share the same color labeling. The black dashed line denotes $\Gamma/2$, where Γ is the relaxation rate. (c-d) Emissivity ε predicted by temporal coupled mode theory (CMT) when (c) there is no magnetic field and (d) when there is 3 T magnetic field. The coupled mode theory uses resonance frequency in (a) and decay rates in (b).

In contrast, the external decay rate has strong dependence on the magnetic field. As shown by Fig. 2(b), without magnetic field, the external decay rate is much smaller than the intrinsic decay rate, leading to weak emissivity. As the magnetic field increases, at $\theta > 0$, the external decay rate increases, leading to its improved matching with the intrinsic decay rate. Due to the better matching between the two decay rates, enhanced emissivity is expected, which is consistent with Fig. 1(c). On the other hand, as the magnetic field increases, at $\theta < 0$, the contrast between the two decay rates further increases, suppressing the emissivity (Fig. 1(c)). Figure 2 (c-d) show the emissivity predicted using Eq. 1 from temporal coupled mode theory, with ω_r, γ_i, and γ_e calculated from the dispersion relations without fitting parameters. The coupled mode theory results show excellent agreement with calculation based on fluctuational electrodynamics. Therefore, the opposite changes of the external decay rates at $\theta > 0$ and $\theta < 0$ in response to the magnetic field lead to strong asymmetry in emissivity profile with respect to θ under magnetic field, i.e., $\varepsilon(\omega, \theta) \neq \varepsilon(\omega, -\theta)$. Moreover, as $\alpha(\omega, \theta) = \varepsilon(\omega, -\theta)$ in specular emitters [*35, 52*], such asymmetry in emissivity with respect to θ directly requires breaking of the Kirchhoff's law of thermal radiation, i.e., $\alpha(\omega, \theta) \neq \varepsilon(\omega, \theta)$. It is noteworthy that when the magnetic field is sufficiently high, which is about 3 T in this case, raising the magnetic field further leads to an increase of external decay rate at all angles, indicating the existence of an optimal magnetic field for breaking the reciprocity between emissivity and absorptivity.

IV. Broadband nonreciprocal emission in gradient epsilon-near-zero magneto-optical metamaterial

Building upon the thin film emitter, we now introduce a general approach for achieving broadband nonreciprocal emission by using gradient epsilon-near-zero (ENZ) magneto-optical metamaterial. The structure consists of magneto-optical multilayer on top of a reflector, as shown in Fig. 3(a). In the multilayer, the ENZ condition for the magneto-optical material is met at progressively shorter wavelength as the depth increases. In such way, as shown by Fig. 3(b), when the permittivity of one magneto-optical layer reaches near zero, the magneto-optical layer immediately underneath it has a negative permittivity, corresponding to the case of one magneto-optical layer (Fig. 1). Nonreciprocal emission due to Berreman mode of each magneto-optical layer can then lead to a broadband nonreciprocal emission.

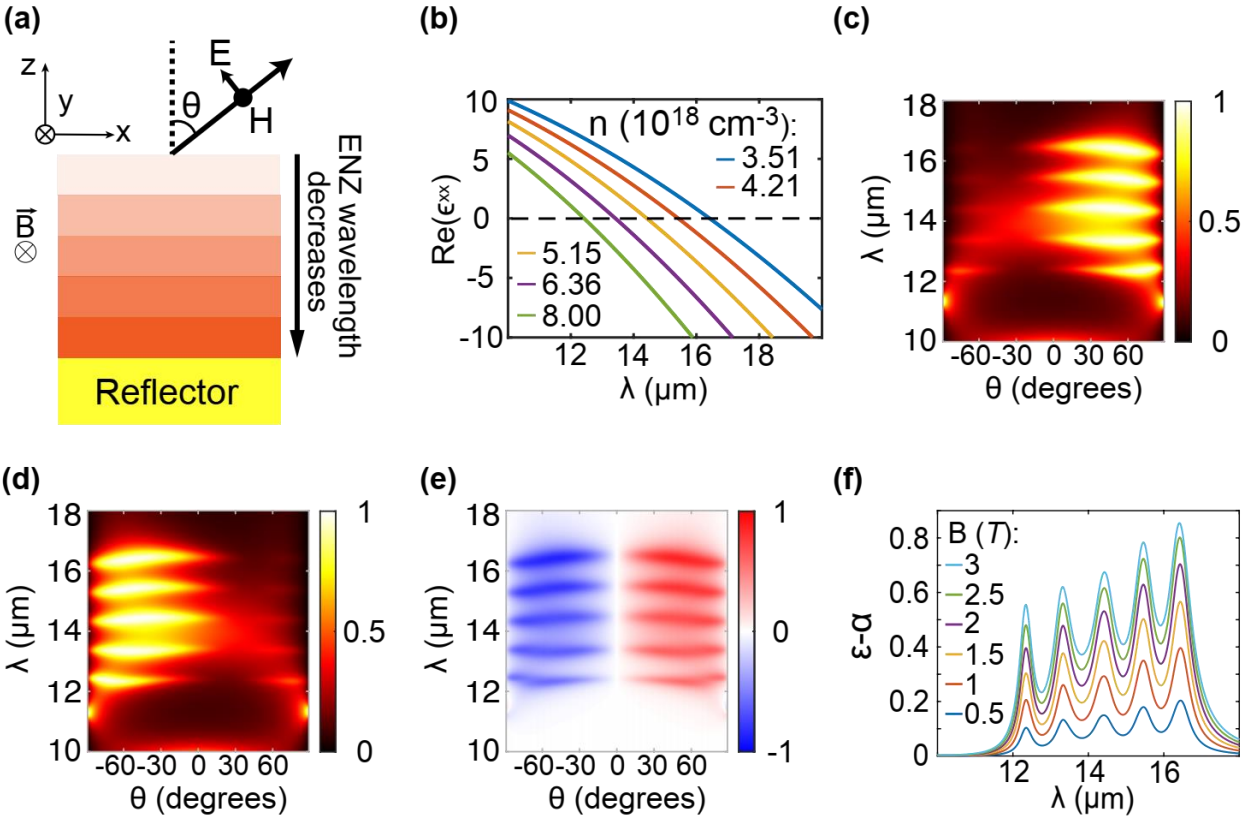

FIG. 3. Broadband nonreciprocal emitter based on gradient epsilon-near-zero magneto-optical metamaterial. (a) Schematic of a gradient epsilon-near-zero magneto-optical metamaterial, on top of a reflector, where the ENZ wavelength of magneto-optical layer decreases with depth. (b) The real part of permittivity (ϵ_{xx}) of doped InSb as a function of wavelength for varying doping levels, at a magnetic field of 3 *T*. In (c-d), we consider gradient-doped InSb multilayer, where the doping level increases with depth. Each doped InSb layer is 400 nm thick, with the corresponding doping level shown in (b). The reflector consists of 500 nm-thick undoped InSb atop Au. (c) Emissivity ε, (d) absorptivity α, and (e) difference between emissivity and absorptivity ($\varepsilon - \alpha$) of the gradient-doped InSb multilayer under 3 *T* magnetic field. (f) Difference between emissivity and absorptivity of the muiltilayer at $\theta = 50^{\circ}$ under varying magnetic fields from 0.5 *T* to 3 *T*.

We numerically demonstrate broadband nonreciprocal emission using a gradient-doped semiconductor multilayer. To make the ENZ wavelength of doped semiconductor decrease with the depth, the doping level of the semiconductor is chosen to increase with the depth. As an example, we consider gradient-doped InSb multilayer, with electron doping levels as $3.51 \times 10^{18}\ cm^{-3}$, $4.21 \times 10^{18}\ cm^{-3}$, $5.15 \times 10^{18}\ cm^{-3}$, $6.36 \times 10^{18}\ cm^{-3}$, and $8 \times 10^{18}\ cm^{-3}$, respectively, and with a 400 nm thickness for each layer. In this multilayer, when the permittivity of a specific layer is near zero, the layer immediately underneath is metallic with relative permittivity about -2, corresponding to the thin film case in Fig. 1. The multilayer is backed by a reflector consisting of 500 nm-thick undoped InSb dielectric spacer layer on top of Au. The spacer layer is used to enhance the nonreciprocal emission contributed by the bottom doped layer. Figure 3(c) and (d) show the emissivity and absorptivity of the multilayer, respectively, at 3 *T* magnetic field. There is strong broadband emission at angle $\theta > 0$, corresponding to ENZ wavelengths of each individual doped layer. In contrast, the absorptivity is negligible for light incident at angle $\theta > 0$. Therefore, emissivity exceeds absorptivity over a broad band at $\theta > 0$, as shown in Fig. 3(e). In contrast, at angle $\theta < 0$, absorptivity exceeds emissivity. Finally, we note substantial difference between emission and absorption already exists at smaller magnetic fields. Figure 3(f) shows the difference between emissivity and absorptivity at $\theta = 50^{\circ}$ under varying magnetic

fields. At $\theta = 50^\circ$, the difference between emissivity and absorptivity reaches 0.85 under 3 T magnetic field, but is already significant as 0.40 under 1 T magnetic field.

Our approach of using gradient ENZ magneto-optical metamaterial for achieving broadband nonreciprocal emission is general. In the following, we show another broadband nonreciprocal emitter based on magnetic Weyl semimetals (MWS) [*53-56*]. Magnetic Weyl semimetals can break the Lorentz reciprocity without external magnetic field due to strong anomalous Hall effect associated with enhanced Berry curvature near Weyl nodes. MWS recently have been used to theoretically design nonreciprocal emitters without external magnetic field [*36, 37*], though experiments of nonreciprocal emitters based on MWS await to be demonstrated. We consider a multilayer emitter which consists of five MWS layers with gradient chemical potential on top of Au, as shown in Fig. 4(a). In MWS, the separation $2\boldsymbol{b}$ between two Weyl nodes in the momentum space acts similar to internal magnetization. When the momentum separation of Weyl nodes is aligned in y axis, the relative permittivity tensor of MWS is given by:

$$\overleftrightarrow{\epsilon} = \begin{bmatrix} \epsilon_d & 0 & -i\epsilon_a \\ 0 & \epsilon_d & 0 \\ i\epsilon_a & 0 & \epsilon_d \end{bmatrix},$$

where $\epsilon_a = \frac{be^2}{2\pi^2\hbar\omega}$. The diagonal term ϵ_d has the form:

$$\epsilon_d = \epsilon_b - \frac{ir_s g}{6\Omega_0}\Omega G\left(\frac{\Omega}{2}\right) - \frac{r_s g}{6\pi\Omega_0}\left\{\frac{4}{\Omega}\left[1 + \frac{\pi^2}{3}\left(\frac{k_B T}{E_F(T)}\right)^2\right] + 8\Omega\int_0^{\xi_c}\frac{G(\xi) - G\left(\frac{\Omega}{2}\right)}{\Omega^2 - 4\xi^2}\xi d\xi\right\}.$$

We follow Ref. [*57*] for the dielectric model of MWS. Here, ϵ_b is the background permittivity, $r_s = \frac{e^2}{4\pi\epsilon_0\hbar v_F}$ is the effective fine-structure constant where v_F is the Fermi velocity, $\Omega = \frac{\hbar(\omega + i\tau^{-1})}{E_F}$ is the normalized complex frequency where τ is the scattering time and $E_F(T)$ is the chemical potential as a function of temperature T, $\Omega_0 = \frac{\hbar\omega}{E_F}$ is the normalized real frequency, and $G(E) =$

$n(-E) - n(E)$ where $n(E) = \frac{1}{e^{\frac{E-E_F}{k_B T}}+1}$ is the Fermi-Dirac distribution and k_B is the Boltzmann constant. Following Refs. [*57, 58*], we use $b = 8.5 \times 10^8\ m^{-1}$, $\epsilon_b = 6.2$, $v_F = 0.83 \times 10^5\ m\ s^{-1}$, $g = 2$, $\xi_c = 3$, and $\tau = 450\ fs$. With nonzero momentum separation, the permittivity tensor of WMS becomes asymmetric, breaking the Lorentz reciprocity. We consider MWS multilayer, where each layer has a thickness of 100 nm, and its chemical potential increases with depth, as 29 meV, 46 meV, 61 meV, 78 meV, and 99 meV, respectively. As the chemical potential increases, the ENZ wavelength shifts to shorter wavelength, as shown in Fig. 4(b).

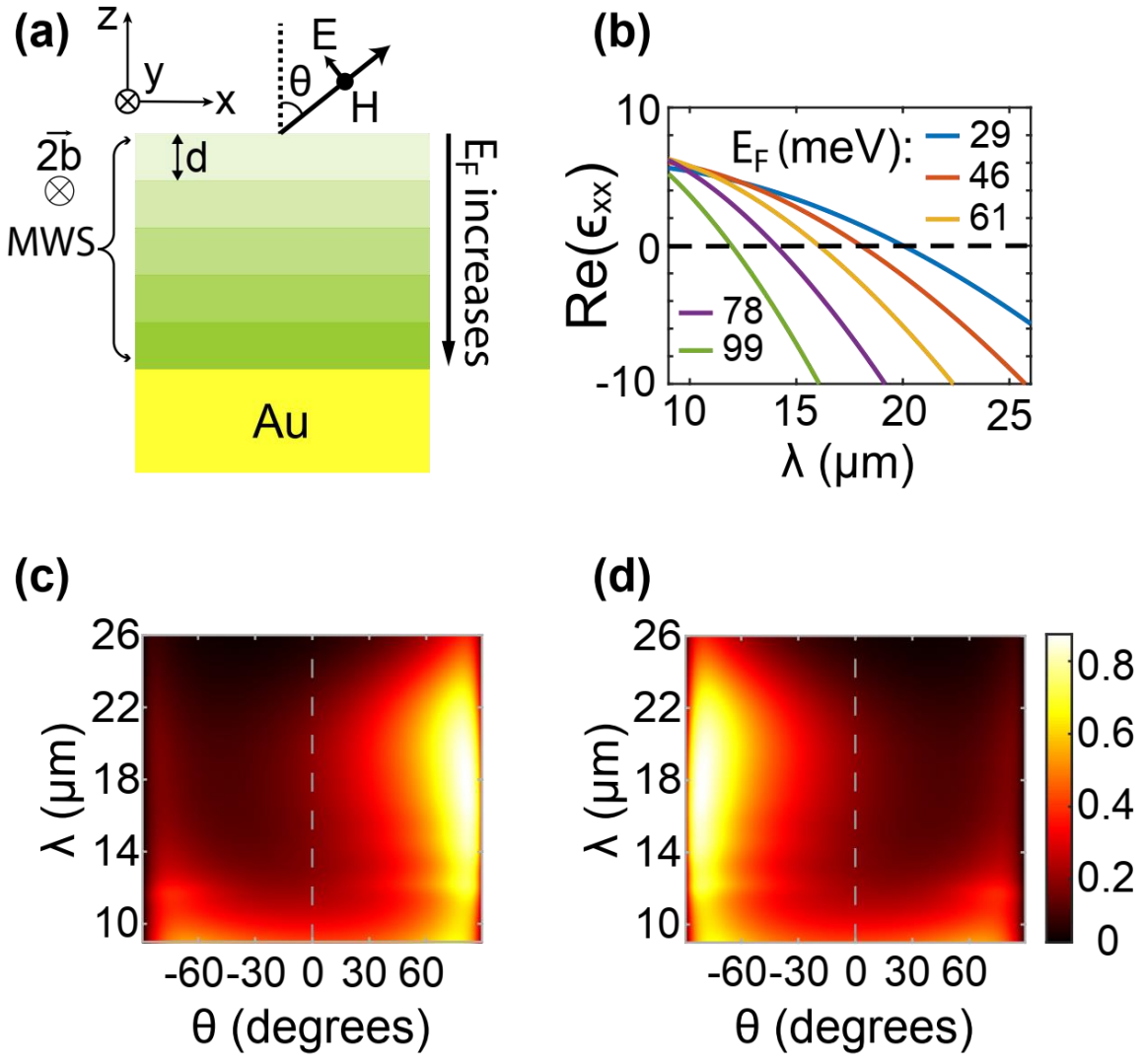

FIG. 4. Broadband nonreciprocal emitter based on magnetic Weyl semimetal (MWS) metamaterial. (a) Schematic of the emitter consisting of MWS layers with gradient chemical potential atop Au. Each MWS layer has a thickness of $100\ nm$, and its chemical potential increases with depth. (b) The real part of permittivity tensor component ϵ_{xx} as a function of wavelength λ for varying chemical potentials at $T = 300\ K$. (c) Emissivity ε and (d) absorptivity α of the MWS multilayer with gradient chemical potential.

We show the calculated emissivity and absorptivity of the MWS multilayer in Fig. 4 (c-d). The MWS multilayer with gradient chemical potential shows strong broadband emission at $\theta > 0$, but negligible absorption at the same angles, leading to broadband nonreciprocal emission and absorption. In contrast, the structure shows negligible emissivity at $\theta < 0$, but strong broadband absorption at the same angles. The achieved spectral bandwidth of nonreciprocal emission is as large as 10 μm. The gradient chemical potential for MWS may be achieved experimentally via doping [*59-61*] through controlling the types and concentrations of dopants.

We compare the broadband nonreciprocal emitters based on semiconductors and those based on magnetic Weyl semimetals. First, nonreciprocal emitters based on magnetic Weyl semimetals typically have a broader spectral bandwidth than those based on semiconductors. For the diagonal element of the relative permittivity, when its real part is near zero, its imaginary part is ~0.01 and ~1 for semiconductors and magnetic Weyl semimetals, respectively. As a larger imaginary part for the permittivity at ENZ wavelength indicates larger intrinsic loss, emitter based on magnetic Weyl semimetals has broader bandwidth compared with that based on semiconductors. Second, the angular responses of the two emitters are different. The emitter based magnetic Weyl semimetals has a narrower angular range than that based on semiconductors. Further, the emission of broadband nonreciprocal emitter based on magnetic Weyl semimetals peaks at larger angle compared with that based on semiconductors. Finally, the broadband nonreciprocal emitter based on semiconductor requires external magnetic field. In contrast, the broadband nonreciprocal emitter based on magnetic Weyl semimetal is possible to function without external magnetic field.

V. Conclusion and Discussion

In conclusion, we have introduced a general approach to achieve broadband nonreciprocal emission and absorption by using gradient epsilon-near-zero magneto-optical metamaterial. We use temporal coupled mode theory to elucidate nonreciprocal emission and absorption in one magneto-optical layer. We then introduce gradient epsilon-near-zero magneto-optical metamaterial as a general way for achieving broadband angle-selective nonreciprocal emission and absorption. We numerically demonstrate broadband nonreciprocal thermal emission in gradient-doped semiconductor multilayer under magnetic field, as well as in magnetic Weyl semimetal multilayer with gradient chemical potential without external magnetic field. Our results will be useful for designing broadband nonreciprocal emitters and absorbers for improving energy conversion, such as for solar cells, thermophotovoltaics, harvesting outgoing thermal radiation, and for achieving nonreciprocal radiative thermal management and communication.

Finally, we provide a brief discussion on a few aspects towards application of broadband nonreciprocal emitters including working temperature, operating wavelength, and requirement on magnetic field. We start by discussing the working temperature of broadband nonreciprocal emitters. In this work, we considered broadband nonreciprocal emitters at 300 K. First, we numerically demonstrated broadband nonreciprocal emitters based on InSb, due to its low electron effective mass, and thus a large cyclotron frequency at a given magnetic field. InSb has a melting temperature of 800 K. We note that the material choice for achieving broadband nonreciprocal emission is quite general. Semiconductors [*62*] such as InAs, $InGa_{0.47}As_{0.53}$, GaAs, HgTe, PbTe, PbSe, and PbS, which have a low effective mass, could be used to achieve similar effects. These semiconductors have melting temperatures near or higher than 1000 K. Second, certain magnetic Weyl semimetals have high Curie temperatures, such as Co_2MnGa at 690 K [*53*] and Co_2MnAl at

726 K [*63*]. Thus, broadband nonreciprocal emitters based on semiconductors and Weyl semimetals have potential to work over a large temperature range. We note as temperature changes, the optical properties of semiconductors and magnetic Weyl semimetals will change, and thus the design will need to be modified.

We discuss the operating wavelength of broadband nonreciprocal emitters. In our work, as numerical examples, we demonstrated broadband nonreciprocal emission at wavelengths about 10-20 μm. Depending on the applications, the wavelength range for nonreciprocal emission and absorption needs be tailored. For solar energy harvesting and thermophotovoltaics, broadband nonreciprocal emission is required at wavelengths shorter than 10 μm. For harvesting outgoing radiation from an ambient at 300 K to the outer space, broadband nonreciprocal emission is needed at the mid infrared. Further, for nonreciprocal heat flux control and communication, the wavelength range of nonreciprocal emission depends on the temperature of the bodies, and communication frequency, respectively. The wavelength range can be shifted to shorter (or longer) wavelengths by increasing (or reducing) the doping concentration of semiconductors, and by increasing (or reducing) the Fermi level of magnetic Weyl semimetals.

We further discuss the requirement for magnetic field for achieving broadband nonreciprocal emission. For broadband nonreciprocal emitters based on semiconductors, the difference between emissivity and absorptivity reaches 0.85 under 3 T magnetic field, but is already significant as 0.40 under 1 T magnetic field. We note that in a recent experiment [*64*], magnetic field of similar magnitude (1.2 T) was generated using ferromagnets to achieve nonreciprocal absorption. Further, we showed that magnetic Weyl semimetals have potential to support broadband nonreciprocal emission without using any magnetic field. Thus, our general

strategy for achieving broadband nonreciprocal emission will be useful and relevant for experiments and applications.

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