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## ABSTRACT

Recently, nonreciprocal structures that violate Kirchhoff's law of thermal radiation have attracted considerable interest for their potential in solar energy harvesting applications. However, previous research has primarily focused on mid-infrared wavelengths rather than on the main solar wavelength range where sunlight intensity is concentrated. In this work, we theoretically demonstrate a nonreciprocal structure operating within the main solar spectrum, specifically tailored to meet the requirements of solar cell applications.





Conventional research on solar energy harvesting typically assumes reciprocal systems, where a body's spectral directional emissivity and absorptivity are equal. This balance between emissivity and absorptivity is also known as Kirchhoff's law of thermal radiation.[1] However, reciprocity of a system introduces a fundamental loss mechanism for solar energy harvesting. Kirchhoff's law implies the emission of photons to the Sun, and such emissions are inevitably wasted. This loss prevents solar cell systems from maximizing power efficiency and makes it impossible to reach the ultimate theoretical efficiency limit of solar energy harvesting.[2–8]

In recent years, there has been increasing interest in utilizing optical nonreciprocity to enhance solar cell efficiency beyond the limits of conventional reciprocal systems.[6–10] The main idea is to direct the emitted photons away from the Sun, rather than back toward it, and transfer the emitted photons to another solar cell, allowing them to contribute to additional electrical energy generation. This approach, which requires a violation of Kirchhoff's law, can reduce photon energy waste and improve overall efficiency. Importantly, in this approach, since the emission spectrum from a solar cell is relatively narrow and is concentrated on the band edge, it is sufficient to achieve Kirchhoff's law violation only over a narrow frequency range.

A standard method to passively break a system's reciprocity is to use magneto-optical materials that have permittivity tensor in an asymmetric form.[11,12] A pioneering work on designing such nonreciprocal structures was conducted by Zhu and Fan.[9] They proposed a magneto-optical photonic crystal structure consisting of n-type InAs with an external magnetic field applied to induce a magneto-optical effect. Their structure achieved maximal contrast between absorptivity and emissivity for a specific direction and wavelength.

Numerous studies have since emerged to advance nonreciprocal structures toward practical implementation.[13] Zhao *et al.* proposed a design similar to that of Zhu and Fan, but, with a significantly reduced external magnetic field.[14] The use of magnetic Weyl semimetals, which do not require an external magnetic field to induce a magneto-optical effect, has also been explored.[15–17] In addition, efforts have been made to broaden the bandwidth and angular range of nonreciprocal behavior.[18–21] Furthermore, transmission-based setups for nonreciprocal systems, rather than reflection-based ones, have been proposed, offering a more suitable approach for constructing nonreciprocal multi-junction solar cells.[10,22,23] Recently, Kirchhoff's law violation has been experimentally demonstrated in the infrared wavelength regime.[24–27]

Despite continuous advancements in the field, previously proposed nonreciprocal structures have been limited to operating at wavelengths of or longer than 1.55 $\mu$m,[28] with most functioning in the range of a few to tens of micrometers. However, for nonreciprocal structures to be effectively applied to solar cells, their nonreciprocal behavior must occur within the main solar spectrum range. Assuming the Sun acts as a black body at 6000 K, Fig. 1 shows that at wavelengths above 1.55 $\mu$m, the spectral radiance of the Sun drops to less than 11% of its maximum value. Therefore, for solar cell applications, a device must operate at much shorter wavelengths. Yet, no nonreciprocal structure that operates in the main solar wavelength regime, where solar radiance is sufficiently high, has been reported to date.

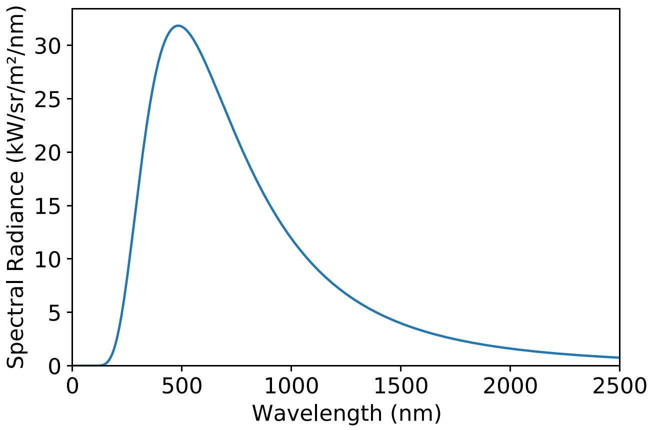


**FIG. 1.** Spectral radiance of a black body at 6000 K.

In addition to the operating wavelength, another important consideration for solar cell applications is the inclusion of semiconductor regions in the structure that can absorb light and convert photon energy into electrical energy. Moreover, for maximum efficiency, the absorption needs to be concentrated exclusively in the semiconductor regions, as light absorbed by other materials will not contribute to electrical energy and will be wasted. Therefore, all other materials, including the magneto-optical material used to break reciprocity, must be lossless.

Demonstrating a nonreciprocal structure that meets these conditions as outlined above would represent a significant step toward the practical application of nonreciprocity in solar cells. In this work, we present a nonreciprocal structure specifically tailored to meet the requirements of solar cell applications.

In the wavelength range between 400 and 1100 nm, terbium gallium garnet (TGG) is a commonly used low-loss material for inducing a magneto-optical effect.[29] For our purpose of designing a nonreciprocal structure that operates within the main solar spectrum, we also select TGG as the magneto-optical material. The relative permittivity tensor of TGG can be represented as

$$\bar{\bar{\varepsilon}} = \begin{bmatrix} \varepsilon_d & 0 & j\varepsilon_a \\ 0 & \varepsilon_d & 0 \\ -j\varepsilon_a & 0 & \varepsilon_d \end{bmatrix}. \tag{1}$$

In this work, we set $\varepsilon_d = 3.8$ and $\varepsilon_a = 4 \times 10^{-5}$. The diagonal element $\varepsilon_d$ is chosen based on the refractive index of TGG reported in the literature.[30] The off-diagonal element $\varepsilon_a$, which determines the strength of the magneto-optical effect, is set to a realistic value achievable with an external magnetic field of approximately 1 T.[30–33] This field strength can be readily generated by strong permanent magnets, such as neodymium magnets.

Despite its widespread use, we note that the magneto-optical effect produced by TGG is relatively weak. In fact, the limited availability of materials capable of providing a strong magneto-optical effect is one of the major obstacles to demonstrating nonreciprocity in the main solar wavelength range. To overcome this challenge and achieve strong nonreciprocal behavior using TGG, we employ a high-quality-factor (high-Q) guided mode resonance.[34] Further details on the guided mode resonance are provided in the discussion of Fig. 2.

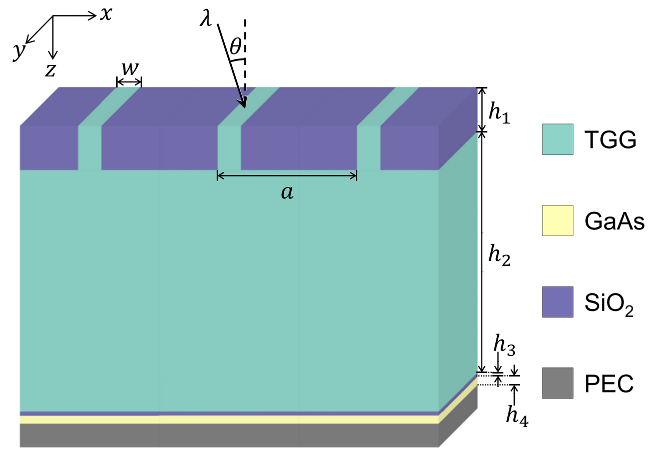


**FIG. 2.** Our nonreciprocal structure for solar cell applications. TGG: terbium gallium garnet, PEC: perfect electric conductor.

For the light-absorbing semiconductor that converts photon energy to electrical energy, we use GaAs, as its bandgap energy lies within the primary solar spectrum range. For its refractive index and extinction coefficient, we refer to data from Ref. 35.

Using these materials, we design a structure that can violate Kirchhoff's law while satisfying the requirements for solar cell applications. Figure 2 shows our structure, with the optimization variables marked. We assume TM-polarized light with wavelength $\lambda$ obliquely incident on the structure at an angle $\theta$ in the $xz$ plane. Our structure is periodic along the $x$ direction with periodicity $a$ and uniform along the $y$ direction. The TGG layer, shown in blue, has a height $h_2$, with its magnetization aligned along the $y$ direction. This magnetization direction is consistent with the permittivity tensor form in Eq. (1). A thin layer of GaAs with thickness $h_4$ is shown in yellow, and this is the only part of the structure where light is absorbed.

In Fig. 2, the top of the structure features a TGG grating with width $w$ and height $h_1$, designed to provide guided mode resonance. The remaining sections of the grating are filled with $SiO_2$, shown in violet. The refractive index of $SiO_2$ is set at 1.47, which is a reasonable value in the wavelength range we are considering.[36] This refractive index is well-suited for creating a high-Q resonance, as a small refractive index variation in the grating enables resonance with a narrow linewidth.[37] This high-Q guided mode resonance allows the nonreciprocal effect to occur even with weak magneto-optical effect.

$SiO_2$ also serves as a spacer between the TGG and GaAs layers with a height $h_3$, allowing for adjustment of the distance between these layers to achieve critical coupling, thereby maximizing absorption. At the very bottom, we place a perfect electric conductor (PEC) to ensure reflection without transmission, creating two reflection-related channels, as in the work by Zhu and Fan.[9]

For optimizing our structure, we use a custom-built rigorous coupled-wave analysis (RCWA) tool.[38–42] This tool is designed to handle anisotropic materials with $3 \times 3$ tensor permittivity for magneto-optical regions.[43–46] Using this tool, we determine the absorptivity and emissivity for each scenario and employ a genetic algorithm to identify the optimal parameter values that maximize the contrast between absorptivity and emissivity for a specific direction and wavelength.

TABLE I. Optimization variables and their optimized results.

| Variable | Description | Optimized result |
|---|---|---|
| $\lambda$ | Light wavelength | 923.5848 nm |
| $\theta$ | Incidence angle | 17.7° |
| $a$ | Periodicity along $x$ direction | 552 nm |
| $w$ | TGG width in TGG-$SiO_2$ grating | 93 nm |
| $h_1$ | TGG-$SiO_2$ grating height | 175 nm |
| $h_2$ | TGG layer height | 956 nm |
| $h_3$ | $SiO_2$ spacer height | 16 nm |
| $h_4$ | GaAs layer height | 32 nm |

The list of optimization variables and their optimized values are summarized in Table I. Figure 2 is drawn to scale, using the geometric parameters shown in Table I.

Figure 3 shows the absorptivity and emissivity spectra of our optimized nonreciprocal structure for TM-polarized incident light at an incidence angle of 17.7°. Due to the magneto-optical effect, the absorptivity and emissivity resonance peaks are split, indicating the violation of Kirchhoff's law. This splitting results in a contrast of about 0.935 between absorptivity and emissivity at a wavelength of 923.5848 nm. This wavelength falls within the main solar spectrum range and is close to the band edge of GaAs, making it well-suited as the light-absorbing semiconductor in this design. We note that the resonances illustrated in Fig. 3 are very narrow, enabling significant contrast between absorptivity and emissivity to occur even with the small resonance splitting resulting from the weak magneto-optical effect of TGG.

The magnetic field distribution within the structure under the maximum absorptivity–emissivity contrast condition is displayed in Fig. 4. For TM-polarized light, the magnetic field is oriented along the $y$ direction, which is perpendicular to the plane. In Fig. 4(a), we observe a strong magnetic field, indicating significant absorption in the light incidence direction marked by the arrow. In contrast, Fig. 4(b) shows a weak magnetic field in the opposite light incidence direction, indicating minimal absorption. It has been shown in Ref. 47 that the contrast in the two field distributions here is directly related to the effects of Kirchhoff's law violation. This illustrates the nonreciprocal behavior dependent on the direction of light propagation and explains the results shown in Fig. 3.

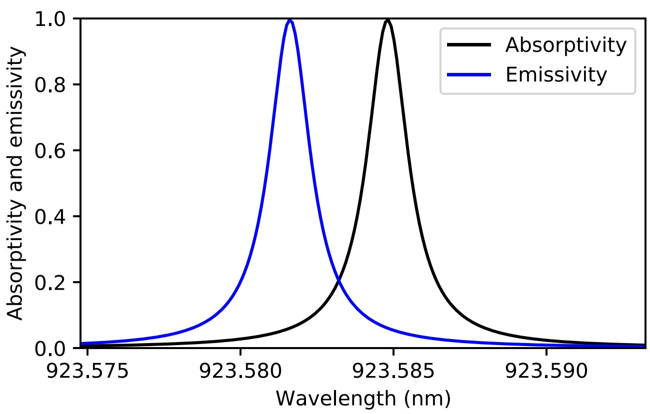


FIG. 3. Absorptivity and emissivity spectra of our optimized nonreciprocal structure for TM-polarized light incident at an angle of 17.7°.

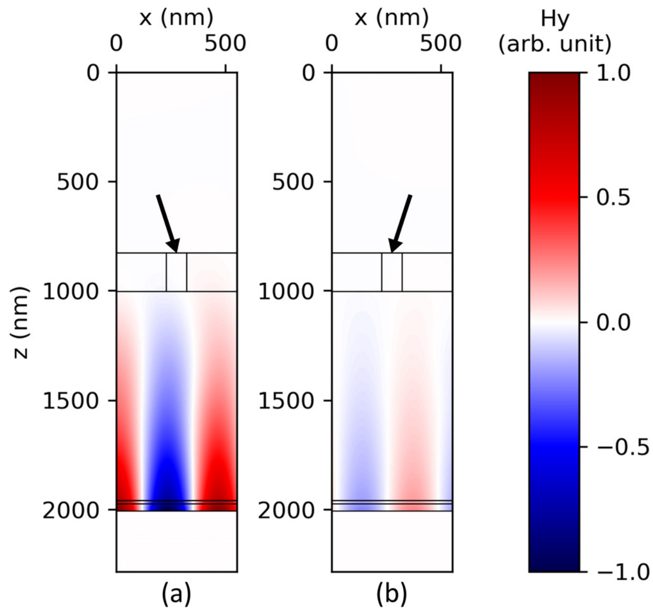


FIG. 4. Magnetic field distribution under the maximum absorptivity–emissivity contrast condition. The magnetic field is perpendicular to the plane due to TM-polarized incident light. (a) Incidence angle of 17.7°. (b) Incidence angle of −17.7°.

In conclusion, we theoretically demonstrate nonreciprocal emission and absorption behavior within the primary solar wavelength range to meet the requirements of solar cell applications. Using TGG as the magneto-optical material and GaAs as the semiconductor, we achieve nonreciprocity through narrow guided mode resonance, even with the weak magneto-optical effect of TGG. The optimization steps in our work are general, allowing a similar process to be applied to find other optimal designs with different parameters. For example, as a follow-up research, we expect that a semitransparent nonreciprocal structure[10,22,23] suitable for solar cell applications may also be designed using a similar optimization approach. Moreover, developing methods to achieve a more pronounced magneto-optical effect in the main solar wavelength range would simplify the design and allow nonreciprocity to occur over a broader bandwidth, representing a promising direction for future work. Our work shows that nonreciprocal behavior can be achieved in the main solar wavelength regime that is important for solar cell applications, laying the groundwork for future research to further advance nonreciprocity applications in solar energy harvesting.

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## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

## Author Contributions

**Yubin Park:** Conceptualization (equal); Investigation (equal); Methodology (equal); Software (equal); Visualization (equal); Writing – original draft (equal). **Shanhui Fan:** Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Supervision (equal); Writing – review & editing (equal).

## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## REFERENCES


[1] G. Kirchhoff, "On the relation between the radiating and absorbing powers of different bodies for light and heat," London, Edinburgh, Dublin, Philos. Mag. J. Sci. **20**, 1–21 (1860).

[2] A. D. Vos, "Detailed balance limit of the efficiency of tandem solar cells," J. Phys. D **13**, 839 (1980).

[3] A. De Vos and H. Pauwels, "On the thermodynamic limit of photovoltaic energy conversion," Appl. Phys. **25**, 119–125 (1981).

[4] H. Pauwels and A. De Vos, "Determination of the maximum efficiency solar cell structure," Solid-State Electron. **24**, 835–843 (1981).

[5] P. T. Landsberg and G. Tonge, "Thermodynamic energy conversion efficiencies," J. Appl. Phys. **51**, R1–R20 (1980).

[6] H. Ries, "Complete and reversible absorption of radiation," Appl. Phys. B **32**, 153–156 (1983).

[7] M. Green, *Third Generation Photovoltaics: Advanced Solar Energy Conversion, Springer Series in Photonics* (Springer-Verlag, Berlin, Heidelberg, 2003).

[8] M. A. Green, "Time-asymmetric photovoltaics," Nano Lett. **12**, 5985–5988 (2012).

[9] L. Zhu and S. Fan, "Near-complete violation of detailed balance in thermal radiation," Phys. Rev. B **90**, 220301 (2014).

[10] Y. Park, B. Zhao, and S. Fan, "Reaching the ultimate efficiency of solar energy harvesting with a nonreciprocal multijunction solar cell," Nano Lett. **22**, 448–452 (2022).

[11] D. Jalas, A. Petrov, M. Eich, W. Freude, S. Fan, Z. Yu, R. Baets, M. Popović, A. Melloni, J. D. Joannopoulos, M. Vanwolleghem, C. R. Doerr, and H. Renner, "What is – and what is not – an optical isolator," Nat. Photonics **7**, 579–582 (2013).

[12] V. S. Asadchy, M. S. Mirmoosa, A. Díaz-Rubio, S. Fan, and S. A. Tretyakov, "Tutorial on electromagnetic nonreciprocity and its origins," Proc. IEEE **108**, 1684–1727 (2020).

[13] S. Yang, M. Liu, C. Zhao, S. Fan, and C.-W. Qiu, "Nonreciprocal thermal photonics," Nat. Photonics **18**, 412–424 (2024).

[14] B. Zhao, Y. Shi, J. Wang, Z. Zhao, N. Zhao, and S. Fan, "Near-complete violation of Kirchhoff's law of thermal radiation with a 0.3T magnetic field," Opt. Lett. **44**, 4203–4206 (2019).

[15] B. Zhao, C. Guo, C. A. C. Garcia, P. Narang, and S. Fan, "Axion-field-enabled nonreciprocal thermal radiation in Weyl semimetals," Nano Lett. **20**, 1923–1927 (2020).

[16] S. Pajovic, Y. Tsurimaki, X. Qian, and G. Chen, "Intrinsic nonreciprocal reflection and violation of Kirchhoff's law of radiation in planar type-I magnetic Weyl semimetal surfaces," Phys. Rev. B **102**, 165417 (2020).

[17] Y. Tsurimaki, X. Qian, S. Pajovic, F. Han, M. Li, and G. Chen, "Large nonreciprocal absorption and emission of radiation in type-I Weyl semimetals with time reversal symmetry breaking," Phys. Rev. B **101**, 165426 (2020).

[18] B. Zhao, J. Wang, Z. Zhao, C. Guo, Z. Yu, and S. Fan, "Nonreciprocal thermal emitters using metasurfaces with multiple diffraction channels," Phys. Rev. Appl. **16**, 064001 (2021).

[19] Z. Zhang and L. Zhu, "Broadband nonreciprocal thermal emission," Phys. Rev. Appl. **19**, 014013 (2023).

[20] C. Du and B. Zhao, "Controlling the ENZ profile for broadband nonreciprocal thermal emitters with high contrast between emissivity and absorptivity," in *Proceedings of the 10th International Symposium on Radiative Transfer* (Begel House Inc., 2023).

[21] J. Wu, Y. Sun, B. Wu, Z. Wang, and X. Wu, "Extremely wide-angle nonreciprocal thermal emitters based on Weyl semimetals with dielectric grating structure," Case Stud. Therm. Eng. **40**, 102566 (2022).

[22] Y. Park, V. S. Asadchy, B. Zhao, C. Guo, J. Wang, and S. Fan, "Violating Kirchhoff's law of thermal radiation in semitransparent structures," ACS Photonics **8**, 2417–2424 (2021).

[23] M. F. Picardi, V. I. Moerbeek, M. Pascale, and G. T. Papadakis, "Nonreciprocity in transmission mode with planar structures for arbitrarily polarized light [Invited]," Opt. Mater. Express **14**, 2201–2209 (2024).

[24] K. J. Shayegan, S. Biswas, B. Zhao, S. Fan, and H. A. Atwater, "Direct observation of the violation of Kirchhoff's law of thermal radiation," Nat. Photonics **17**, 891–896 (2023).

[25] K. J. Shayegan, B. Zhao, Y. Kim, S. Fan, and H. A. Atwater, "Nonreciprocal infrared absorption via resonant magneto-optical coupling to InAs," Sci. Adv. **8**, eabm4308 (2022).

[26] M. Liu, S. Xia, W. Wan, J. Qin, H. Li, C. Zhao, L. Bi, and C.-W. Qiu, "Broadband mid-infrared non-reciprocal absorption using magnetized gradient epsilon-near-zero thin films," Nat. Mater. **22**, 1196–1202 (2023).

[27] S. Pajovic, Y. Tsurimaki, X. Qian, G. Chen, and S. V. Boriskina, "Nonreciprocal reflection of mid-infrared light by highly doped InAs at low magnetic fields" arXiv:2410.06596 (2024).

[28] M. Q. Liu and C. Y. Zhao, "Near-infrared nonreciprocal thermal emitters induced by asymmetric embedded eigenstates," Int. J. Heat Mass Transfer **186**, 122435 (2022).

[29] D. Vojna, O. Slezák, A. Lucianetti, and T. Mocek, "Verdet constant of magneto-active materials developed for high-power faraday devices," Appl. Sci. **9**, 3160 (2019).

[30] E. G. Víllora, P. Molina, M. Nakamura, K. Shimamura, T. Hatanaka, A. Funaki, and K. Naoe, "Faraday rotator properties of $\{Tb_3\}[Sc_{1.95}Lu_{0.05}](Al_3)O_{12}$, a highly transparent terbium-garnet for visible-infrared optical isolators," Appl. Phys. Lett. **99**, 011111 (2011).

[31] M. Y. A. Raja, D. Allen, and W. Sisk, "Room–temperature inverse Faraday effect in terbium gallium garnet," Appl. Phys. Lett. **67**, 2123–2125 (1995).

[32] F. Guo, J. Ru, H. Li, N. Zhuang, B. Zhao, and J. Chen, "Growth and magneto-optical properties of $LiTb(MoO_4)_2$ crystal," Appl. Phys. B **94**, 437–441 (2009).

[33] O. Slezák, R. Yasuhara, A. Lucianetti, and T. Mocek, "Temperature-wavelength dependence of terbium gallium garnet ceramics Verdet constant," Opt. Mater. Express **6**, 3683–3691 (2016).

[34] S. Fan and J. D. Joannopoulos, "Analysis of guided resonances in photonic crystal slabs," Phys. Rev. B **65**, 235112 (2002).

[35] K. Papatryfonos, T. Angelova, A. Brimont, B. Reid, S. Guldin, P. R. Smith, M. Tang, K. Li, A. J. Seeds, H. Liu, and D. R. Selviah, "Refractive indices of MBE-grown $Al_xGa_{(1-x)}As$ ternary alloys in the transparent wavelength region," AIP Adv. **11**, 025327 (2021).

[36] L. Gao, F. Lemarchand, and M. Lequime, "Refractive index determination of $SiO_2$ layer in the UV/Vis/NIR range: Spectrophotometric reverse engineering on single and bi-layer designs," J. Eur. Opt. Soc.: Rapid. Publ. **8**, 13010 (2013).

[37] S. S. Wang and R. Magnusson, "Theory and applications of guided-mode resonance filters," Appl. Opt. **32**, 2606–2613 (1993).

[38] M. G. Moharam and T. K. Gaylord, "Rigorous coupled-wave analysis of planar-grating diffraction," J. Opt. Soc. Am. **71**, 811–818 (1981).

[39] M. G. Moharam, E. B. Grann, D. A. Pommet, and T. K. Gaylord, "Formulation for stable and efficient implementation of the rigorous coupled-wave analysis of binary gratings," J. Opt. Soc. Am. A **12**, 1068–1076 (1995).

[40] P. Lalanne and G. M. Morris, "Highly improved convergence of the coupled-wave method for TM polarization," J. Opt. Soc. Am. A **13**, 779–784 (1996).

[41] G. Granet and B. Guizal, "Efficient implementation of the coupled-wave method for metallic lamellar gratings in TM polarization," J. Opt. Soc. Am. A **13**, 1019–1023 (1996).

[42] L. Li, "Use of Fourier series in the analysis of discontinuous periodic structures," J. Opt. Soc. Am. A **13**, 1870–1876 (1996).

[43] K. Rokushima and J. Yamakita, "Analysis of anisotropic dielectric gratings," J. Opt. Soc. Am. **73**, 901–908 (1983).

[44] L. Li, "Reformulation of the Fourier modal method for surface-relief gratings made with anisotropic materials," J. Mod. Optic. **45**, 1313–1334 (1998).
[45] L. Li, "Fourier modal method for crossed anisotropic gratings with arbitrary permittivity and permeability tensors," J. Opt. A **5**, 345 (2003).
[46] B. Caballero, A. García-Martín, and J. C. Cuevas, "Generalized scattering-matrix approach for magneto-optics in periodically patterned multilayer systems," Phys. Rev. B **85**, 245103 (2012).
[47] C. Guo, B. Zhao, and S. Fan, "Adjoint Kirchhoff's law and general symmetry implications for all thermal emitters," Phys. Rev. X **12**, 021023 (2022).