Kirchhoff's law violation within the main solar wavelength range [F]

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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.

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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 μm,[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 μm, 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.
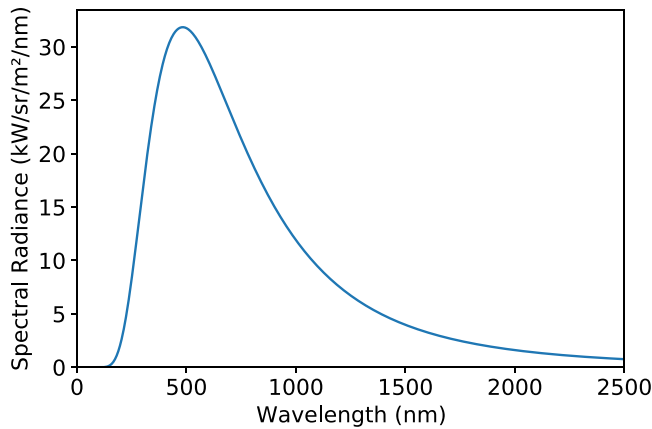
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FIG. 1. Spectral radiance of a black body at 6000 K.

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

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

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

In this work, we set $\varepsilon_d = 3.8$ and $\varepsilon_a = 4 \times 10^{-5}$. The diagonal element ε_d is chosen based on the refractive index of TGG reported in the literature.[30] The off-diagonal element ε_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.
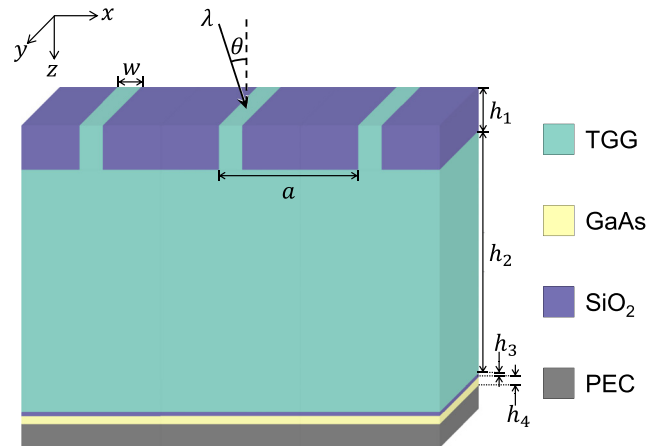
For the light-absorbing semiconductor that converts photon energy to electrical energy, we use GaAs, as its bandgap energy lies within the primary solar spectrum range. For its refractive index and extinction coefficient, we refer to data from Ref. 35.

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 λ obliquely incident on the structure at an angle θ 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 3×3 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
λ	Light wavelength	923.5848 nm
θ	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
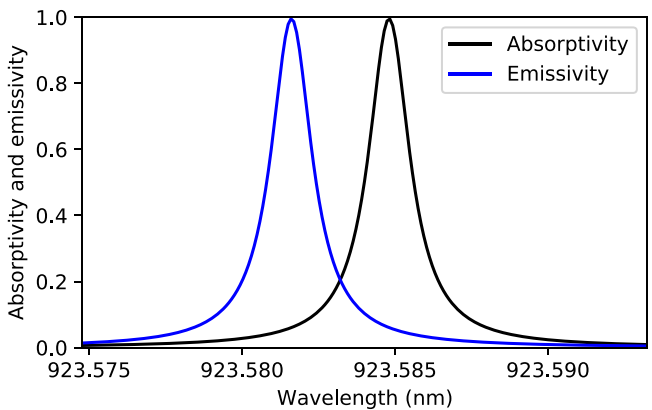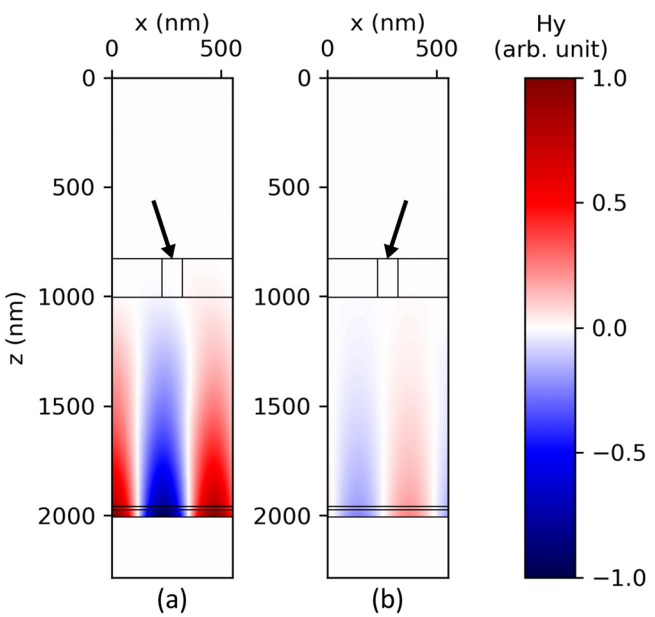

FIG. 4. Magnetic field distribution under the maximum absorptivity–emissivity contrast condition. The magnetic field is perpendicular to the plane due to TM-polarized incident light. (a) Incidence angle of 17.7°. (b) Incidence angle of −17.7°.

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.

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.

AUTHOR DECLARATIONS
Conflict of Interest

The authors have no conflicts to disclose.

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

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.

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14 December 2024 12:00:58