Circularly polarized thermal emission from chiral metasurface in the absence of magnetic field

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Abstract. We report on the thermal radiation source which emits circularly polarized thermal radiation in the absence of an external magnetic field. The geometry of thermal source includes a photonic crystal slab waveguide with chiral morphology. We show that due to the absence of a mirror symmetry of such metasurface, the thermally generated electromagnetic waves are circularly polarized with the circular polarization degree of 0.87. Using the Fourier modal method we study the structure eigenmodes and analyze the field distributions in them.

1. Introduction

In recent years, the study of thermal emission of periodic materials attracted a great deal of attention from researchers due to its high potential for important applications in near- and far-field thermal management [1, 2]. Usually, the thermal radiation from bulk emitters is incoherent, broadband and isotropic. By changing the emitter symmetry one can control the angular emission diagram and the polarization of thermal radiation. In particular, a structure without a mirror symmetry can emit circularly polarized thermal radiation. The mirror symmetry can be broken down by applying an external magnetic field due to spin-orbit interaction of electrons. Another way to break down the mirror symmetry is creating a structure with a chiral surface morphology. Chiral metasurfaces were used in literature to obtain the circularly polarized photoluminescence of quantum dots [3]. The highest theoretically predicted circular polarization degree was as high as 99% while the corresponding experimental value was 81%. The circular polarization degree depends on the surface geometry and is a matter of theoretical optimization.

Here we use the chiral metasurface to generate the circularly polarized thermal radiation. We demonstrate a structure with artificial rotational anisotropy which radiates the circularly polarized thermal emission and discuss this effect in detail.

2. Model structure and theory

In this paper, the thermal emitter consists of a KCl substrate capped by ZnSe waveguide with two-dimensional array of etched gammadions (Fig. 1a). The bottom surface of rectangles is covered by 40-nm thick layer of Si₃N₄. In this work we are focused on the 7–15 µm wavelength range. ZnSe and KCl are transparent in the middle infrared range and hence do not contribute to the thermal emission. In contrast, Si₃N₄ has a wide absorption band and hence is the source of thermal radiation in the structure.
Figure 1. (a) Schematics of chiral metasurface and (b) its single period. (c): LCP (blue) and RCP (red) emissivity spectra of the chiral metasurface.

Figure 2. Circular polarization degree is shown by green. Geometrical parameters of the metasurface are the following: $a = 12.3\,\mu m$, $b = 6.1\,\mu m$, $c = 3.3\,\mu m$, $h_1 = 9.8\,\mu m$, $h_2 = 40\,nm$, $h_3 = 4.8\,\mu m$.

The emissivity is calculated by the Kirhoff’s law which states that the absorptivity and emissivity are equal. This has been numerically verified for uniform and photonic crystal slabs[4]. The absorptivity is calculated using the Fourier modal method in the scattering matrix form [5, 6, 7, 8]. The decompositions of electric and magnetic fields into Fourier series were done using Li’s factorization rules [9] with $13 \times 13 = 169$ spatial harmonics. We checked the accuracy of the method with up to $31 \times 31 = 961$ spatial harmonics for most important results.

3. Results and discussions

To demonstrate the circularly polarized thermal emission, we calculate the emissivity spectra of chiral metasurface in left circular polarization (LCP) and right circular polarization (RCP) as well as the circular polarization degree (CPD). We estimate the CPD as

$$\eta = \frac{I_{RCP} - I_{LCP}}{I_{RCP} + I_{LCP}}$$

As shown in Fig. 2, in the displayed spectral range, the emissivity spectra are characterized by the peaks at $\lambda \approx 13\,\mu m$ which have different amplitudes in LCP and RCP. In the result, the circular polarization degree at this wavelength is non-zero and reaches the values of 0.87.

To understand the origin of the resonance behavior of emissivity, we notice that the homogeneous layer of ZnSe represents a waveguide since it’s surrounded by the layers of smaller
refractive index \(^1\). As we recently demonstrated in Ref. [10] for similar structure, the peaks in the emissivity spectra originate from the eigenmodes of the this waveguide. Due to the metasurface periodicity, these eigenmodes, called as quasiguided modes, are visible in the far field of thermal radiation.

The dispersions of emissivity in RCP and LCP as well as the dispersion of the CPD is shown in Fig. 3. It can be seen from Fig. 3(a,b) that there are several families of quasiguided modes near the \(\Gamma\)-point of the photonic crystal lattice. We notice that the quasiguided modes have different widths. This difference can be understood by inspecting the electric field distributions of these modes.

![Figure 3](image)

\textbf{Figure 3.} Calculated dispersions of the emissivity in (a) RCP and (b) LCP and (c) of the degree of circular polarization.

![Figure 4](image)

\textbf{Figure 4.} Distributions of electric field intensity in the chiral metasurface eigenmodes A and B specified in the Fig. 3. (a), (c): XZ-cross sections at \(y = 4\mu m\); (b), (d) XY-cross sections at \(z = h_1 + h_2/2\). Blue lines denote the material boundaries. Two periods along X- and Y- axis are shown.

Fig. 4 shows the electric field intensity distribution in two modes in \(\Gamma\)-point, namely \((a/\lambda)_A = 0.91 - 0.0014i\) and \((a/\lambda)_B = 0.86 - 0.006i\). It can be seen from Fig. 4(a) that the mode A is mainly localized in the homogeneous ZnSe layer almost not penetrating into the absorptive Si\(_3\)N\(_4\). In \(1\) The capping photonic crystal layer has an effective refractive index smaller than that of ZnSe since it has the air inclusions.
contrast to the mode A, the mode B is located both in the periodic and homogeneous parts of the structure (Fig.4(b)) and by this being affected by absorption in Si$_3$N$_4$ material. Another reason for the difference in the modes quality factors is that the mode B is coupled to the far field better than the mode A. As a result, the mode B has shorter lifetime and lower quality factor. The mode profiles within the emitting Si$_3$N$_4$ layer are shown in Fig.4(c,d).

As explained in detail in Ref. [10], all the modes in Fig. 3 originate from transverse electric (TE) and transverse magnetic (TM) eigenmodes of the effective planar waveguide, a first and rough approximation of our chiral metasurface. Hence, the thicknesses of modulated and non-modulated parts of the structure, $h_1$ and $h_3$, should influence drastically on that modes. To illustrate this, we calculate the DCP of thermal emission at $\lambda = 13 \mu m$ as a function of the thicknesses $h_1$ and $h_3$ (see Fig. 5, red-blue image graph and the colormap on the right). The interaction between the resonances of the homogeneous ZnSe layer with the resonances of the entire structure results in quite complicated $h_1$ and $h_3$ dependency of the degree of circular polarization.

**Figure 5.** Degree of circular polarization as a function of thicknesses $h_1$ and $h_3$.

The angular emission diagram of circularly polarized thermal radiation is shown in Fig. 6 for $\lambda = 13 \mu m$. The pronounced red spot in the center of Fig. 6(c) indicates the strong circular polarization of thermal emission towards the normal to the metasurface. Another off-normal emissivity peaks correspond to the quasiguided modes.

**Figure 6.** Angular thermal emission diagram of chiral metasurface calculated at $\lambda = 13 \mu m$ in (a) RCP and (b) LCP and (c) the degree of circular polarization.

4. **Conclusion**

In conclusion, we have demonstrated that the chiral metasurface can emit the circularly polarized thermal radiation with the circular polarization degree as high as 87%. We attribute this effect
to the shape anisotropy of the photonic crystal part of the structure.

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