Broadband mid-infrared non-reciprocal absorption using magnetized gradient epsilon-near-zero thin films

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The study of magneto-optical absorption has stimulated diverse energy-technology-related explorations, showing potential in breaking the current theoretical efficiency limits of energy devices compared with reciprocal counterparts. However, experimentally realizing strong infrared non-reciprocal absorption remains an open challenge, and existing proposals of non-reciprocal absorbers are restricted to a narrow working waveband. Here we observe highly asymmetric absorption spectra over a broad mid-infrared band (nearly 10 μm) using doped InAs multilayers with gradient epsilon-near-zero frequencies. We reveal that the magnetized epsilon-near-zero behaviours and material loss play important roles in achieving strongly non-reciprocal absorption under a moderate external magnetic field using a thin epsilon-near-zero film (<λ/40, λ is the wavelength). Our approach enables flexible control over the working frequencies and non-reciprocal bandwidths by designing magnetized InAs films with different doping concentrations. The proposed principles can also be generalized to other III–V semiconductors, magnetized metals, topological Weyl semimetals, magnetized zero-index metamaterials and metasurfaces.

Magneto-optics combined with nanophotonics1–4 has become an active research area in recent decades due to its essential role in several important applications, including sensing5, unidirectional waveguides4, optical isolators and modulators5,6. In the past years, many interests have been focused on experimentally enhancing magneto-optical (MO) effects at the nanoscale by taking advantage of magnetized surface plasmon polaritons in structured plasmonic materials7–9 or Mie-type resonances in dielectric nanostructures8, to introduce a large modulation of intensity, phase or polarization of transmission or reflection light. For these studies, one of the basic considerations is to mitigate the adverse impact from intrinsic ohmic losses in devices so as to improve the MO efficiency, that is, both intensity and relative changes in transmissivity or reflectivity in transverse magneto-optical Kerr effects. Although the importance of free-space

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MO absorption behaviours, which show potential in several energy applications\(^\text{10–13}\), has been long neglected.

Although the physics of non-reciprocal absorption/emission has been discussed in bulk magnetized materials\(^\text{4–16}\) dating back to the 1970s, realizing strong non-reciprocal absorption/emission still lacks comprehensive studies in theory, experiments and applications. More recently, non-reciprocal absorption in magnetized nanostructures has gained increasing attention in the area of non-reciprocal thermal photonics\(^\text{7–26}\) (Supplementary Fig. 1 shows the roadmap), promising several revolutional technologies in energy applications (mainly in near- to mid-infrared regions) like non-reciprocal energy-harvesting devices\(^\text{10}\), non-reciprocal multijunction photovoltaic cells\(^\text{22}\) and non-reciprocal thermophotovoltaics\(^\text{13–16}\). For these MO devices, Kirchhoff’s law of thermal radiation\(^\text{20}\), which originates from Lorentz reciprocity\(^\text{20}\) and indicates the equality of spectral/angular emissivity \(e(\omega,\theta)\) and absorptivity \(a(\omega,\theta)\) (\(\omega\) and \(\theta\) are the angular frequency and incident angle, respectively), is expected to be invalid, enabling to break the constraint of energy conversion limits in reciprocal counterparts and approach thermodynamic limits\(^\text{21,22}\).

Despite the potential in both fundamental theory and applications, few works can experimentally realize non-reciprocal absorbers/emitters with strong MO responses in infrared regions. Besides, how to realize broadband non-reciprocity in these MO energy devices is also important due to the broadband nature of thermal radiation. One of the pioneering works for designing non-reciprocal infrared absorbers/emitters was theoretically proposed\(^\text{6}\), where MO n-InAs one-dimensional photonic crystals were considered. When an external magnetic field \(B\) is applied along the \(z\) axis, the permittivity of MO InAs film \((t = 700 \text{ nm})\) on a perfect electric conductor substrate in the lossless limit, under different values of \(B\): black (0 T), yellow (0.5 T), blue (1.0 T) and purple (1.5 T).

Fig. 1 | Schematics of non-reciprocal absorption control. a. Compared absorption spectra of reciprocal (left) and non-reciprocal (right two) absorbers. The overlapped spectra are separated in the presence of \(B\). b. Schematic of a single magnetized InAs thin film (thickness \(t\)) atop the reflective high-doped InAs substrate. The external magnetic field \(B\) is applied along the \(z\) direction. Here \(\theta\) is the incident angle in the experiments. c. Dielectric permittivity of the fabricated InAs film with \(n_{\text{in}}\) and \(\mu\) at \(B = 0\) T. d. Dispersion relation of a magnetized InAs film (\(t = 700 \text{ nm}\)) on a perfect electric conductor substrate in the lossless limit, under different values of \(B\): black (0 T), yellow (0.5 T), blue (1.0 T) and purple (1.5 T). e. Evolution of the reflection phase and asymmetric absorption spectra of the structure in b with \(t = 700 \text{ nm}\) as the magnitude of the damping rate \(\Gamma = 5.9 \times 10^3 \text{ rad s}^{-1}\) (material loss) changes. The pentagrams denote the perfect absorption points, corresponding to phase singularities with ±1 topological invariants.
transverse magneto-optical Kerr effects; however, the working frequencies are restricted to the terahertz, narrow-visible or near-infrared bands. More recently, mid-infrared non-reciprocal absorption spectra were measured by adding dielectric gratings on a thick InAs wafer, but the non-reciprocity can only be observed within a narrow and fixed working band (<17 μm). As compared in Supplementary Fig. 2 and Supplementary Table 1, among the areas of classical magneto-optics (transverse magneto-optical Kerr effects in reflection and transmission) and emerging non-reciprocal thermal photonics (non-reciprocal absorption), the infrared non-reciprocal working waveband is limited and cannot be flexibly tuned. On the other hand, another important issue is the working waveband (or working frequency) around the ENZ frequency. The roles of material loss, doping concentration and thickness of the ENZ layer in engineering highly asymmetric absorption have been revealed. Especially, we propose a principle to design broadband non-reciprocal absorbers (Fig. 1a) whose working waveband and bandwidth can be flexibly tuned over a wide range based on the magnetized ENZ platforms. Various non-reciprocal absorbers with different shapes of asymmetric absorption spectra have been fabricated and measured.

As shown in Fig. 1b, we first consider an opaque and non-reciprocal thermal absorber composed of a thin InAs film (thickness t) with a doping concentration n, epitaxially grown atop a high-doped InAs substrate (n, = 1.6 × 10^17 cm^-3, electron mobility μ, = 7,890 cm^2 V^-1 s^-1). Methods provides details of the sample fabrication. Figure 1c gives the permittivity of one fabricated InAs film calculated by the measured values of n, = 7.4 × 10^16 cm^-3 and μ, = 9,000 cm V^-1 s^-1 (Supplementary Section 2), showing a zero crossing at ω_Ε = 7.56 × 10^13 rad s^-1. Here the high-doped InAs substrate serves as a metal-like reflector within the waveband of interest (-16.8–27.3 μm; Supplementary Fig. 4b) and also ensures a better quality of deposited InAs films

![Image](https://doi.org/10.1038/s41563-023-01635-9)
due to the lattice-matching mechanism. Such a thin ENZ film on a reflective substrate is capable of supporting guided modes under transverse-magnetic polarization ($E_x, K_y, H_z$), whose dispersion relation is governed by

$$\tan(\kappa t) = \frac{\kappa e \left( y + \frac{\kappa}{\varepsilon_s} \right)}{\varepsilon_0 k_0^2 - \kappa^2 - \eta \beta \times \left( y - \frac{\kappa}{\varepsilon_s} \right)} = \frac{(\varepsilon^2 - \eta^2) y + \frac{\kappa}{\varepsilon_s}}{\varepsilon_0 k_0^2 - \kappa^2},$$

where $\beta$ represents the propagation constant, $\kappa = \sqrt{k_0^2 + c^2 - \beta^2}$ and $y = \sqrt{\beta^2 - k_0^2}$ ($k_0 = \frac{\omega}{c} = \frac{2n}{\lambda}$ and $c$ is the speed of light in a vacuum). Also, $\varepsilon_s$ is the permittivity of the substrate and $\gamma_s = \sqrt{\beta^2 - k_0^2 \varepsilon_s}$.

Supplementary Section 4 shows the dispersion derivation. Figure 1d compares the dispersion curves of a 700 nm ($t < \lambda/40$) InAs film on a perfect electric conductor substrate ($\frac{\kappa}{\varepsilon_s} \rightarrow 0$) in the lossless limit ($\mu \rightarrow \infty$). The radiative BMs, originally studied by Berreman in 1963, are located within the light cone, which can directly couple with free-space propagating modes and introduce a resonant absorption peak in the far-field absorption/emission spectra. The surface ENZ modes below the light line should also be excited, that is, with the assistance of dielectric gratings. In general, the dispersion profiles are perfectly symmetric for reciprocal cases ($\omega(\theta) = \omega(\theta)$; Fig. 1d, black lines). In the presence of B, the dispersion curve within the light cone experiences a rotation with respect to the centre of (0, $\partial\omega_{ENZ}/\partial\delta\mu$) (Fig. 1d). The rotation centre is also known as the bound state in the continuum in the lossless limit, at which the root and pole of equation (1) are perfectly overlapped. The extent of rotation increases with a higher B. Here the employed high-doped lossy InAs substrate will further introduce a small angular shift away from the rotation centre (Supplementary Section 5). For symmetric wavevectors $\beta(\pm \theta)$, the corresponding frequencies of modes are separated and move along opposite directions as B increases. Such symmetry-broken behaviours provide a new platform to shape non-reciprocal absorption.

Note that the magnitude of material loss in InAs thin films plays an important role in asymmetric absorption manipulation. Before, one was always searching for a high-Q resonance [34], to relieve the requirement of B. In theory, the Q factor of modes is determined by both radiative and non-radiative channels $Q^{-1} = Q_N^{-1} + Q_R^{-1}$, where a high $Q_N$ requires low-loss materials. However, natural MO materials with a large loss will broaden the resonant peaks and make the non-reciprocal phenomena weak. Our recent work [35] has revealed that the presence of material loss in such a system will make the bound state in the continuum (red triangle at $\theta = 0^\circ$; Fig. 1d) split into two phase singularities [36] ($\nu = \frac{\omega}{c} \psi = \pm 1, \psi = \arg(r)$, where $r$ is the reflection coefficient) that exactly correspond to perfect absorption points (a = 1 R = 1 $|r|^2 = 1$) (Fig. 1e, bottom). Increasing the material loss makes the phase singularities move away from the origin of the bound state in the continuum along the dispersion curve, consequently moving out of the light cone and resulting in weak absorption at $\theta$ but high absorptivity maintained at $+\theta$ (Fig. 1e, middle and top; Supplementary Section 6 shows a detailed analysis). Therefore, although the material loss in our experiments is an order of magnitude larger than the values taken in theoretical works [34,35], we still successfully realize a large non-reciprocity in absorption even under a moderate B, benefiting from synergizing MO effects and ENZ properties.

In the following, we measure a series of non-reciprocal absorbers using InAs thin films ($t < 1 \mu$m), to explore the role of asymmetric BM-induced non-reciprocity in absorption/emission. Here we directly show the experimental results of $\alpha(\theta) = 1 - R_{\text{in}}$ in what follows because of $\Delta = \{\alpha(\theta) - \alpha(-\theta)\} = |\alpha(\theta) - \alpha(-\theta)|$ according to energy conservation. The reflectivity spectra were measured by a custom-built infrared MO Kerr effect characterization setup (Fig. 2a). Figure 2b,c compares the measured (dotted lines) and simulated (full lines) non-reciprocal absorption spectra at $\theta = 60^\circ$. There are two types of sample with different $n_e$ values: $n_{e,L} = 7.4 \times 10^{17} \text{cm}^{-3}$ and $n_{e,L} = 6.5 \times 10^{17} \text{cm}^{-3}$; the subtle differences between them can be distinguished in the Raman measurement (Fig. 2d). The non-reciprocal resonant peak experiences a distinct redshift to the low-frequency band (Fig. 2b), since the ENZ frequency of low-$n_{e,L}$ samples moves to $\omega_{ENZ_L} = 7.1 \times 10^{13} \text{rad s}^{-1}$. The grey lines in this figure show the overlapped results ($\Delta = 0$) in the absence of B. A larger thickness ensures a higher value of $\Delta_{\text{max}}(60^\circ)$, whose maximum can be up to 0.63 at $\theta = 900 \text{ nm}$ and $B = 1.5 \text{T}$. The shadowed light-green areas in this figure denote the waveband $\Delta \lambda$ of $\Delta(60^\circ) > 0.3$. In reciprocal systems, there will be an optimal angle (or thickness) where perfect absorption can be available at a fixed thickness (angle). Such behaviours can also be understood from the perspective of phase singularities (perfect absorption points) revealed here, whose spectral and angular positions are influenced by radiative loss of the system [37] that could be modified by the thickness $t$ and angle $\theta$. Similar features can be observed in non-reciprocal systems (Fig. 2c), where the experimental results of $\Delta_{\text{max}}$ are given as functions of B and $t = \theta = 60^\circ$ and $45^\circ$. Supplementary Fig. 13 shows the measured asymmetric absorption spectra of $n_{e,L}$ samples with different thicknesses at $\theta = 45^\circ$. The realized BM-induced non-reciprocal absorption can be preserved over a wide angle. Besides, we also observe non-reciprocal resonant peaks with $\Delta_{\text{max}}(60^\circ) = 0.45$ induced by BMs in the high-doped InAs substrate (Supplementary Fig. 5), whose ENZ frequency is high ($\omega_{ENZ,L} = 11.2 \times 10^{13} \text{rad s}^{-1}$).

As revealed in Fig. 1d, the asymmetric surface ENZ modes below the light line can also be excited in non-reciprocal spectra by adding dielectric gratings sitting on the above InAs thin films ($t = 700 \text{ nm}$) (Fig. 3a). Figure 3b shows the scanning electron microscopy image of fabricated asI gratings with $p_g = 8.00 \mu$m, $t_g = 1.10 \mu$m, $t_e = 0.25 \mu$m and $w_0 = 0.5p_g$, whose simulated asymmetric angle-resolved spectra at $B = 1.5 \text{T}$ are shown in Fig. 3c. Apart from the BM-induced asymmetric resonance at a low-frequency range, there are two other absorption...
InAs interlayer in ref. 19 is on the order of the working wavelength for the guided modes become distinct. For example, the thickness of the layer is denoted as $t$. The ENZ region is shadowed in grey ($\text{Re}(\varepsilon) < 1$). The interval between adjacent lines is $0.1 \times 10^{18} \text{cm}^{-3}$. Simulated angle-resolved non-reciprocal absorption spectra of a 14-layer structure ($t_i = 0.4 \mu m$) with gradient $n_i$ from the bottom to top layers: $n_{\text{InAs}}^+$-$n_{\text{InAs}}^+$-$n_{\text{InAs}}^+$-$n_{\text{InAs}}^+$. Measured and simulated asymmetric absorption spectra of the 14-layer sample at $\theta = 60^\circ$. TEM images of a three-layer sample. The lattice fringe image (top right) and its associated fast Fourier transform (bottom right) are also given on the right. Measured and simulated asymmetric absorption spectra of two three-layer samples at $\theta = 60^\circ$ and $B = 1.5 \text{T}$.

Fig. 4 Broadband non-reciprocal absorbers. a. Schematic of a magnetized ENZ multilayer with gradient $n_i$. The value of doping concentration gradually decreases from the bottom layer. The thickness of the layer is denoted as $t_i$. Real part of permittivity of doped InAs films with different doping concentrations $n_i$. The ENZ region is shadowed in grey ($\text{Re}(\varepsilon) < 1$). The interval between adjacent lines is $0.1 \times 10^{18} \text{cm}^{-3}$. Simulated angle-resolved non-reciprocal absorption peaks owing to asymmetrically folded bands from the dispersion of surface ENZ modes. The surface-ENZ-mode-induced non-reciprocal properties become sensitive to the grating’s period (Supplementary Fig. 14). The separated peaks gradually redshift as the period increases, but the locations of BM-induced non-reciprocal peaks remain robust. Such behaviours ensure us to individually shape two resonant mechanisms. The measured reciprocal spectra are also given in Supplementary Fig. 15 for better comparison. Although our grating structure looks a little bit similar to what was proposed elsewhere, the origins of the guided modes become distinct. For example, the thickness of the InAs interlayer in ref. 19 is on the order of the working wavelength for enhancing MO effects. In contrast, the InAs thin film ($t < \lambda/40$) proposed here ensures the coexistence of two types of non-reciprocal resonance near the ENZ frequency. Note that the period-sensitive non-reciprocal peaks are also susceptible to material loss. In our experiments, the optical index of the deposited aSi is about 3.3 $+ 0.1i$, leading to a wide overlap between $\alpha (\pm 60^\circ)$ at around $\omega = 8.5 \times 10^{12} \text{rad s}^{-1}$ (Fig. 3d). The BM-induced non-reciprocity is still strong with $\Delta \alpha_{\text{max}} (60^\circ) = 0.45$. There is still plenty of room for achieving narrower peaks when lower-loss dielectric materials and more optimized designs can be found and used. Besides, more non-reciprocal resonant peaks can also be available by designing different grating patterns, that is, asymmetric gratings, two-dimensional gratings, meta-units and so on.

Next, we will show that the magnetized ENZ films exhibit outstanding merits in flexibly engineering broadband non-reciprocal properties, which have not been reported yet. In Fig. 4a, we showcase the magnetized ENZ multilayer composed of gradient-doped InAs films (thickness $t_i$). The doping concentration gradually decreases from the bottom to the top, ensuring ENZ properties over a wide band. Since the employed high-doped InAs wafer substrate can only ensure high reflection at a frequency range shorter than $-11.2 \times 10^{13} \text{rad s}^{-1}$ (Supplementary Fig. 4), here we fabricated a non-reciprocal absorber composed of fourteen ENZ layers with $n_i$ ranging from $n_{\text{InAs}} = 1.8 \times 10^{18} \text{cm}^{-3}$ (bottom) to $n_{\text{InAs}} = 0.5 \times 10^{18} \text{cm}^{-3}$ (top) with an interval of $\Delta n_i = 0.1 \times 10^{18} \text{cm}^{-3}$ (Fig. 4b) shows the permittivity change. Figure 4c shows the simulated angle-resolved non-reciprocal absorption spectra ($t_i = 400 \text{nm}$), where highly asymmetric absorption can be observed over a wide frequency and angle range. The corresponding experimental results are given in Fig. 4d measured at $\theta = 60^\circ$, showing broadband properties ($\lambda \geq 0.3$) within the mid-infrared band. One can expect much broader non-reciprocal absorption when considering more gradient-doped MO ENZ layers. Besides, by choosing ENZ layers with selected doping concentrations and thicknesses, it is capable of designing various non-reciprocal absorbers/emitters working at different wavebands. Accordingly, here we also design two three-layer samples with different couples of $n_i$. Figure 4e shows the transmission electron microscopy (TEM) images of a three-layer sample, where the boundary between the InAs substrate and deposited InAs films is clear. The high-resolution TEM image shows perfect lattice distributions, along with the fast Fourier transform image. Because of different doping concentrations
but similar thicknesses, two samples show similar non-reciprocal bandwidth (Δλ₁, (d ≥ 0.3) = 2.9 μm, Δλ₁, (d ≥ 0.3) = 3.0 μm) but different working wavebands (Fig. 4f). All the experimental results fit well with the numerical data. Our methods provide a versatile platform to arbitrarily shape wideband non-reciprocal absorption spectra. Such broadband designs could be immediately applied to several applications, such as thermal illusion, thermal camouflage and so on.

To further evaluate the polarization-sensitive behaviours of the proposed non-reciprocal absorbers, here we also measured and compared the absorption spectra under transverse-electric polarization (Hₓ, kᵧ, Eᵧ). As expected, for single-layer and multilayer magnetized ENZ structures, the obtained absorptivity is consistently equal and extremely low (Supplementary Fig. 18) since there is no MO response for transverse-electric waves. Large non-reciprocity can still be distinct for polarization-averaged absorption spectra. This capability further guarantees the direct thermal emission from the proposed thermal absorbers/emitters with desirable non-reciprocal behaviours.

In conclusion, we have provided experimental evidence that strongly non-reciprocal absorption spectra can be realized under a moderate magnetic field using ENZ thin films (<1/40). The excitation of asymmetric BMs in a deeply sub-wavelength ENZ film provides a versatile platform to design various non-reciprocal absorbers/emitters, in which the magnitude of material loss, doping concentration and thickness of ENZ layer play important roles in engineering the shape and position of the asymmetric absorption peaks. Especially, we propose a method to realize broadband non-reciprocal absorption/emission using multilayer structures with gradient ENZ frequencies. The broadband and highly asymmetric absorption spectra have also been observed, whose non-reciprocal waveband can be up to 10 μm in the mid-infrared region. Besides, the working waveband and non-reciprocal bandwidth can be flexibly tuned by choosing different couples of ENZ layers. The proposed concepts and mechanism revealed here for tailoring non-reciprocal absorption can also be extended to other III–V semiconductors like GaAs, InP, magnetized metals, topological Weyl semimetals or metamaterials and metasurfaces combined with MO effects, like hyperbolic metamaterials 47, zero-index metamaterials 48. More importantly, our results lay a solid experimental foundation for more comprehensive and general studies in non-reciprocal absorption control, which will breed possibilities in innovating several non-reciprocal energy devices like photovoltaic cells 11 and thermophotovoltaics 12,13.

**Online content**

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41563-023-01635-9.

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Methods

Photonic structure fabrication
The InAs materials were grown using a VG Semicon V90 gas source molecular beam epitaxy system. A VG thermo-cell with two heat zones was used for In sources to reduce the surface oxide defects. The group V source was obtained by cracking arsine (AsH₃) to As, at 1,000 °C. Elemental silicon was used as an n-type dopant. The two-inch n-type substrates used here were S-doped (100) InAs with a carrier concentration of ~1.6 × 10¹⁸ cm⁻³ and a thickness of 500 μm. Before growth, a heat treatment at 365 °C for 3 min under the molecular beam of As, was carried out to remove the surface oxide. Then, the InAs epitaxial layers were grown on InAs substrates at a growth temperature of 360 °C. The InAs growth rate and doping were controlled by changing the temperature of the In cell and the temperature of the Si cell, respectively. In our experiments, the growth rate for InAs layers was kept at 1 μm h⁻¹. The epitaxial layer thicknesses for the samples discussed in Fig. 2 are 200, 700 and 1,000 nm with expected doping concentrations of 8 × 10¹⁷ and 7 × 10¹⁷ cm⁻³. The doping levels of the samples were calibrated by Hall measurements for InAs samples grown on semi-insulating InP substrates. Note that, in the main text, we use the fitting values of $n_{As} = 7.4 × 10^{18}$ cm⁻³ (Fig. 2c) and $n_{In} = 6.5 × 10^{18}$ cm⁻³ (Fig. 2b) and the measured thicknesses. For grating structures, the amorphous silicon layer was deposited via magnetron sputtering. A gold-coated mid-infrared enhanced plane mirror (PF20-03-M02, Thorlabs) was used to reflect the light by 90°. Then, a 90° off-axis parabolic mirror coated with silver (MPD249H-P01, Thorlabs) was used to deflect the beam. A pair of 30° off-axis parabolic mirrors with a focal length of ten inches (MPD2103-P01, Thorlabs) were used to focus the beam on the sample surface and to collect the reflected light from the sample, respectively. Finally, another 90° off-axis parabolic mirror was utilized to focus the light onto the detector. A static magnetic field was applied parallel to the sample surface and perpendicular to the incident plane using a custom-built electromagnet with a maximum applied magnetic field up to 2 T. Different strengths of magnetic fields could be achieved by controlling the magnitude of the current. Further, the intensity of the magnetic field was also strongly related to the distance between two magnetic poles. A gaussmeter was placed in the middle of the poles and in close proximity to the sample so that the specific value of the magnetic field applied to the sample could be obtained. For background calibration, the reflectivity of a silicon wafer coated with a 200-nm-thick gold film was first measured on the setup and considered as unity. The samples’ reflectivity spectra were normalized to this background. Each reflection spectrum in this paper was presented by the average value of three consecutive measurements on the same sample. The error bars were the standard deviation of these measurements.

Data availability
The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions
M.Q.L., C.Y.Z. and C.-W.Q. conceived the ideas. M.Q.L. performed the simulations and advised about the experimental design. L.B. and H.L. led the experiments. W.J.W. fabricated the samples. M.Q.L. performed the optical characteristic measurements. S.X. performed the optical measurements. M.Q.L., S.X., J.Q., H.L., L.B. and C.-W.Q. analysed the data and all the authors discussed the results. M.Q.L. wrote the paper with inputs and comments from all authors. H.L., L.B., C.Y.Z. and C.-W.Q. supervised the project.

Competing interests
The authors declare no competing interests.

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