Large-Area, Broadband, Wide-Angle Plasmonic Metasurface Absorber for Midwavelength Infrared Atmospheric Transparency Window

Weiwei Yu, Yue Lu, Xiren Chen, Hao Xu, Jun Shao, Xin Chen, Yan Sun,* Jiaming Hao,* and Ning Dai

High performance broadband absorbers in the midinfrared atmospheric transparency windows are of great importance in various applications, such as energy harvesting, photodetection, radiative cooling, and stray light elimination. In recent years, great efforts have been made to develop absorbers using plasmonic nanostructured resonators in the infrared regime. Although these approaches promise distinct advantages in performance enhancement, they still suffer several obstacles, e.g., limitations on sample size, bandwidth, and fabrication throughput. Here, a large-area broadband wide-angle plasmonic metasurface absorber with nearly perfect absorption over the range of midwavelength infrared atmospheric transparent window (3–6 µm) is proposed and experimentally demonstrated. The metasurface absorber is basically comprised of a monolayer of sub-micrometer-sized polystyrene spheres self-assembled on an opaque metallic substrate and coated with metal–insulator–metal three-layer thin film, and fabricated by using simple, low-cost self-assembly techniques. Numerical simulation analyses not only corroborate the experimental observations, but also discover that such broadband absorption effect is attributed to hybrid plasmonic multiple resonances. The combination of the significant light absorption effect, compact design, and high-yield self-assembly fabrication process suggests that the proposed absorber has wide prospect application in integrated optical and optoelectronic systems.

1. Introduction

Midwavelength infrared (MWIR) corresponds to the electromagnetic radiation in the wavelength regions from 3 to 6 µm, which is also referred to as intermediate infrared. Demand for new technology of high performance absorption associated with this band is quickly growing, since the portion of this electromagnetic radiation can transmit through the earth's atmosphere without any distortion or absorption in which the homing devices are used extensively for a wide variety of applications, such as photodetection, energy harvesting, radiative cooling, plasmonic printing, environmental monitoring, satellite remote sensing, stray light elimination, and astronomical observation. Previously, various optical engineering structures, such as photonic crystals, optical cavities, and metallic gratings, have been widely investigated to enhance electromagnetic wave absorption. Plasmonic metasurfaces constructed by artificially engineered subwavelength meta-atoms have also been suggested to function as super absorbers. In particular, after the first metasurface-type absorber demonstrated in microwave frequency region with single band absorption, much effort has so far been done to address the narrowband limitation and develop broadband absorbers for midinfrared. For example, Cui et al. proposed a thin film infrared slab made of saw-toothed anisotropic metasurfaces, and predicted a high level of absorption above 95% with the spectral range from 3 to 5.5 µm. Bouchon et al. combined four square patch metal–insulator–metal (MIM) resonators within a subwavelength period, and experimentally demonstrated a broadband absorption of light between 7 and 9.5 µm and an average measured absorbance of 70%. However, although these strategies have been successfully demonstrated to absorb light efficiently covering the infrared atmospheric transparent window (ATW) spectral ranges, the fabrication of such structured absorbers generally relies on top-down techniques such as focused ion beam, electron-beam lithography, or high-resolution photolithography, which renders them difficult to produce with large areas and hence limiting their applications.
Self-assembly technique, as a promising alternative fabrication approach, has been proposed to achieve large-area, low-cost plasmonic and metamaterial absorbers. In demonstration of such an approach, robust spectrally selective absorption in visible and near-infrared wavelengths was recently achieved by using a metasurface composite created by chemically synthesized colloidal Ag nanoparticles deposited onto a thin polymer spacer layer backed with an opaque metal film. A high performance, ultrabroadband plasmonic absorber that operates over the visible to infrared regime was also fabricated based on self-assembly of metallic nanoparticles into a 3D porous membrane. Nevertheless, these scenarios are also subject to some limitations that would hinder them for above midinfrared absorption applications. For the former case, the absorption effect is decided by the surface plasmon resonances associated with the intrinsic properties of the metallic nanoparticles. It is known that metals, whether gold, silver, and aluminum, exhibit plasmonic resonances at ultraviolet or visible frequencies, but in infrared frequencies they behave as superior mirrors. Such idea is thus hardly to extend to midinfrared for broadband absorption. For the latter plasmonic nanostructure, although it possesses high efficiency broadband absorption over a broad range of infrared wavelengths, the thickness of the device is much larger than the operating wavelengths, this is beyond the scope of metasurfaces and unfavorable for application in compact nanophotonic systems.

In this work, we demonstrate a large-area plasmonic metasurface absorber (PMA) with nearly perfect absorption covering the range of MWIR ATW based on a simple, low-cost self-assembly technique. Our broad absorber consists of a five-layer metal–spheres–metal–insulator–metal (MSMIM) thin film, where the second layer is a monolayer of self-assembled sub-micrometer-sized polystyrene spheres (PSs). The measured absorption spectrum shows that absorbance of higher than 90% is achieved over the range from 3 to 6 µm, and the bandwidth (the ratio of the full width at half maximum (FWHM) to the center frequency of the spectrum) is about 125% that exceeds two octaves. Good absorption performance is maintained even at large incident angles. The operating wavelength is easily tunable by alternating the structural dimensions. Numerical simulation analyses not only confirm the rationality of the experimental results, but also reveal that such broadband absorption effect is ascribed to hybrid plasmonic multiple resonances. 2D hyperspectral scanning images indicate that the PMA has truly macroscopic area.

2. Results and Discussion

The preparation of the absorber through self-assembly technique is fairly straightforward. We first used argon ion beam-assisted sputtering (AIBS) to deposit a 100 nm thick gold film on a cleaned silicon wafer, followed by immersing the gold-coated substrate into a Langmuir–Blodgett trough to form ordered PS arrays on the surface of the gold film (see the Experimental Section). This self-assembly method allows us to produce homogeneous, nearly defect-free monolayer of PS arrays with area sizes in square centimeters. Figure 1a–c shows a schematic diagram of the structure at this stage and a side cross-section view and top view scanning electron microscopy (SEM) images of a sample fabricated with 500 nm diameter polymeric spheres. Large-area SEM images of the sample are presented in Figure S1 (Supporting Information). As determined from the SEM images (Figure 1c; Figure S1a, Supporting Information), the polymeric spheres are not contacted with each other closely and separated with the average space 50 nm. It has been reported that such a structure would supports high quality factor multiple Mie-resonance-based modes at the visible and near-infrared wavelength regions. While both experimental and theoretical absorbance spectra show that the structure exhibits high reflection and low absorption within the region of our interest (λ > 1.5 µm), as shown in Figure 1d,e. The reason for this is that the wavelengths we concerned here are far beyond the region of existence of such Mie-resonance-based modes, in other words, for the light with wavelength larger than 1.5 µm, these subwavelength polymeric spheres are transparent and the light can directly see the bottom gold film which is highly reflective. Details of the experiments and the numerical simulations are provided in the Experimental Section.

To enhance the absorption, we then deposited a gold thin film (with 5 nm thickness) on the top of the polymeric spheres to form a metal–spheres–metal (MSM) plasmonic structure (see the Experimental Section), as illustrated in Figure 1f. Corresponding cross-section view and top view SEM images of a fabricated sample after this step are shown in Figure 1g,h. The spectra of measured reflectance and absorbance are presented in Figure 1i. As one can see, the structure exhibits an absorption peak of 91% at the wavelength of ~2.9 µm, and the absorption band has an FWHM of ~115%, which is much broader than those of conventional MIM plasmonic absorbers. Numerical simulations were performed for this structure and are plotted in Figure 1j. It is manifest that the simulated spectra are consistent with the experimental results.

To gain insight into the characteristic of the MSM structure, additional numerical simulations were performed. Figure 2a–f shows the simulated absorbance spectra for a series of distances between the centers of the two adjacent polymeric spheres (p = 940, 880, 780, 740, 660, and 600 nm) at normal incidence, with other parameters fixed as d = 500 nm, and t1 = 16 nm, where d and t1 denote the diameter of polymeric spheres and the thickness of the gold film, respectively. As can be observed, for the large distance (p = 940 nm), the structure has only one resonant absorption peak at 2.3 µm with a much smaller FWHM (40%) compared with the value presented in Figure 1i. As the distance p is decreased, another absorption peak gradually emerges in longer wavelength region accompanied by the reduced absorbance. Figure 2g–l shows the simulated absorbance spectra for six different thickness gold films (t1 = 50, 28, 18, 15, 13, and 5 nm), with other parameters p = 600 nm and d = 500 nm. For t1 = 50 nm case, only one sharp resonant absorption peak is observed at the midinfrared. However, as the thickness of gold film decreases, two absorption peaks increasingly emerge first, and then they merge together to form an absorption peak with broad bandwidth, as shown in Figure 2l (the same case presented in Figure 1j). These results indicate that the absorption peak centered at the wavelength of 2.9 µm as shown in Figure 2l might correspond to a hybrid mode originated from two different plasmonic resonances.

To provide further theoretical insights, we mapped the nearfield distributions at the wavelengths of 2.3 µm denoted by (I)
in Figure 2a, 4.76 µm denoted by (II) in Figure 2g, and 2.9 µm marked as (III) in Figure 2l, where the three strong absorption peaks are observed. As shown in Figure 3a,b (see Figure S2 of the Supporting Information for more details of the near-field distributions), at the wavelength of 2.3 µm, the electric field is mostly distributed around the upper and lower peripheries of the top gold shells, and the magnetic field is strongly confined inside the polymeric spheres, as the structure is excited by a normally incident plane wave with $E_{|| y}$. The field profiles imply that resonance (I) is a typical localized plasmonic mode, similar to the fundamental localized electromagnetic resonant mode supported by conventional MIM absorbers.\cite{30,38} In contrast to the field distribution at resonance (I), both the electric and magnetic fields at 4.76 µm show that the fields are highly concentrated in the gaps between the gold-coated polymeric spheres (see Figure 3c,d), which is analogous to the gap plasmons as reported in previous work.\cite{39} Whereas, for the wavelength 2.9 µm, strong electromagnetic field enhancements not only on the surfaces of the gold shells but also inside the polymeric spheres and the gaps are noted, as plotted in Figure 3e,f. It is obvious that resonance (III) possesses the characteristics of both localized and gap plasmonic modes, demonstrating that the absorption peak at 2.9 µm is really attributed to the plasmonic hybridization of these two resonant modes. Additionally, it is worth to note that as determined from SEM images (Figures 1g and 1f), the deposited gold (5 nm thickness) on the top of polymeric particles displays discontinuous nano-grainlike morphology, this feature would also result in enhancing and broadening of plasmonic absorption. The understanding of the nature of this three-layered structure is fundamentally important to construct broadband absorber with more complicated multilayered structure as presented below.

Although a relatively wide absorption band is obtained based on the above three-layer MSM structure, both the efficiency and bandwidth of the structure are still needed to be improved for achieving the ultimate objective of this work, producing high performance absorber for the entire MWIR ATW. To achieve this goal, we next added two more thin-film layers on the top of the MSM structure (Figure 1k). The one is an $\text{Al}_2\text{O}_3$ dielectric layer, which is synthesized by conformal deposition on the
MSM structure using atomic layer deposition (ALD) technique. The other (top layer) is a gold thin film, which is deposited by AIBS. To develop an optimized device for our purpose, we performed experiments to investigate the absorbance of absorber geometries with different values of the critical geometric parameters. Figure 4a shows the measured absorbance spectra for five different thickness inner gold layers ($t_1 = 4, 5, 7, 9$ and $15$ nm), with other parameters $d = 500$ nm, $h = 50$ nm, and $t_2 = 5$ nm, where $h$, and $t_2$ are the thicknesses of Al$_2$O$_3$ dielectric layer and outer gold layer, respectively. It is noted that as the thickness $t_1$ increases, the absorption efficiency at shorter wavelengths ($\approx 3$ $\mu$m) decreases. This is due to the fact that the absorption at shorter wavelength region is mainly determined by the bottom three layers of the absorber that is analogous to the above MSM structure. The absorption becomes weaker is the result of reduction of coupling between light and the bottom three layers as $t_1$ increases. While, for longer wavelengths ($\approx 6$ $\mu$m), the maximum absorption performance is enhanced and redshifted with increasing thickness $t_1$. This can be explained that the absorption at longer wavelength region is predominantly attributed to the top three layers of the structure that is equivalent to the conventional MIM absorber, where the inner gold layer of the structure functions as the bottom layer of conventional MIM absorber. It has been shown that the layer is normally required to be thick for efficient light trapping. This is why increasing thickness $t_1$ can obviously enhance the absorption performance of the device at longer wavelengths. Figure 4b shows the measured absorbance spectra for five different thickness outer gold layers ($t_2 = 5, 6, 7, 9$, and $14$ nm), with other parameters $t_1 = 4$ nm, $d = 500$ nm, and $h = 50$ nm. As one can see, there exists a critical thickness $t_2 = 5$ nm corresponding to the maximum absorption. For thickness larger than this value, the absorption declined dramatically over a wide wavelength range especially at longer wavelengths as $t_2$ increases. The reason of this behavior is that for the thick outer gold layer, it would block light penetration/coupling into the structure and thus reducing absorption. To confirm the experimental observation, numerical simulations were carried out, and the corresponding results are shown in Figure 4c,d. Reasonable agreements are found between the simulated results and the measured spectra. The discrepancies between these two results might be mainly originated from the fact that the fabricated samples are not exactly in conformity with the simulated ones. In our simulations, such multilayered structures are assumed to have ideal
spherical shapes. However, in reality, during the process of self-assembly deposition, the gold particles are more likely to drop into the gaps between the polymeric spheres, resulting in the part of gold films in the gaps is much thicker than the other on the upper surface of spheres, and forming structures with nonconformal shapes.

The relationships between the absorption properties and the diameter ($d$) of the polymeric spheres and the thickness ($h$) of Al$_2$O$_3$ dielectric layer were also investigated and are presented in Figures S3 and S4 (Supporting Information), respectively. Taking all of these factors into account, the optimized dimensions of an MSMIM PMA covered the entire MWIR ATW are taken as $d = 500$ nm, $t_1 = 4$ nm, $h = 50$ nm, and $t_2 = 5$ nm. Figure 1f–o summarizes the results, including a side cross-section view and top view SEM images, both experimental and computed absorbance and reflectance spectra at normal incidence, of a PMA with above optimized parameters. It is obvious that the absorber exhibits rather broadband absorption with both the measured and simulated absorbance higher than 90% covering the range from 3 to 6 $\mu$m, and a bandwidth of $\approx 125\%$ across more than two octaves.

For many applications, such as light harvesting, thermal imaging and photodetection, angular independent broadband absorption is desirable. Our proposed metasurface-based absorber maintains good broadband absorption performance even for high oblique incident angles resulting from its deep subwavelength configuration and symmetrical geometry. Figure 5a plots the measured absorbance of the sample shown in Figure 1f–n as a function of wavelength and incident angle for unpolarized light. The corresponding simulated absorbance spectrum is presented in Figure 5b. As expected, broadband absorption responses are achieved even at high angles of incidence. Experimental results show that the absorbance remains above 80% over the wavelength range from 3 to 5.4 $\mu$m as the incident angle is increased to 60°. While simulation predicts a relatively higher and broader absorption band, which can cover range from 3 to 6 $\mu$m with absorbance greater than 88% at the incident angle of 60°. We attribute this difference to possible deviation of the fabricated samples from the ideal simulations as well.

In order to understand the nature of broadband absorption in the proposed absorber, near-field responses of the MSMIM PMA at two wavelengths (3 and 6 $\mu$m) were studied based on the similar method adopted in analysis of the MSM structure and are presented in Figures S5 and S6 (Supporting Information). As expected, for the two wavelengths, electromagnetic fields are not only distributed around the surfaces of gold shells and inside the polymeric spheres, but also localized in the gaps between the gold-coated polymeric spheres. The field profiles are even more complicated than the hybridized mode.
shown in Figure 3e,f. This means that such broadband absorption effect relies strongly on the excitation of hybrid plasmonic multiple resonant modes.

Finally, to visually demonstrate the PMA that can work well over large area, we imaged the sample using an infrared microscope connected to a Fourier transform infrared (FTIR) spectrometer. The sample was scanned pixel by pixel automatically with pixel size of 300 \( \mu m \). For each pixel, a wide spectral response (1.5–16 \( \mu m \)) was recorded. A 2D hyperspectral image was eventually generated with 34 pixels along \( x \)-axis and 24 pixels along \( y \)-axis, thus allowing us to fully investigate the absorption property of the sample. Figure 6a shows the measured absorption spectrum of the sample, which is the average value over spectral response of all pixels in the image. In order to further show the spatial and frequency dependence of the PMA, in Figure 6b–e, we plot 3D images of the experimental absorbance data for several typical wavelengths of 1.8, 3, 6, and 8 \( \mu m \). The images are presented as \((x, y, A)\), where the \( x \)- and \( y \)-axis denote the dimensions of the sample, and the \( z \)-axis indicates the absorbance for each pixel. As one can see, the absorbance is mostly equal to a
certain constant over the xy plane in each image, with an exception for a pixel located at the top right corner, since there is a dust (denoted by a circle in the inset on the right of Figure 6a) attached to this pixel affecting its absorption performance. All these results indicate that our device performs quite well as a broadband super absorber over truly macroscopic large area.

3. Conclusion

In summary, we have proposed and experimentally demonstrated a high performance broadband plasmonic metasurface absorber that is fabricated by using self-assembly techniques and able to absorb infrared light from 3 to 6 µm with measured absorption larger than 90%. The metasurface-based absorber is basically comprised of a monolayer of sub-micrometer-sized polystyrene spheres self-assembled on an opaque metallic substrate and coated with metal–insulator–metal three-layer thin film, and produced in large area (cm²) with a total thickness only 659 nm. The absorption is independent of the angle of incidence and can easily be tuned to other wavelength ranges by varying the geometric parameters. Being beneficial from high efficiency, broadband, wide-angle, good performance absorption over large area and deep subwavelength thickness, the presented metasurface absorber can be integrated with available technologies for thermal imaging, infrared detection, and stray light elimination.
4. Experimental Section

Preparation of Ordered Polystyrene Spheres Array: After impurities removing and hydrophilic treatment in a piranha solution (volume ratio of H$_2$O$_2$ and H$_2$SO$_4$ is about 3:7), silicon wafer was immersed in lauryl sodium sulfate (SDS) solution (weight ratio of SDS and water is 10 wt%) for about 12 h to obtain cleaned and hydrophilic surface. Three sizes of the polystyrene spheres (400, 500, and 800 nm in diameter) were used in our experiment. All these polystyrene spheres solutions were purchased from Thermo Fisher scientific Inc. The original PS aqueous solution (1000 Series, 10 wt%, 15 ml) was diluted with an equal amount of ethanol, and then sonicated in an ultrasonic washer until mixing well. Pipetted 30 µL PS suspension solution on the pretreated silicon wafer, which would spread out on the silicon wafer and form an evenly distributed PS film. After dried at room temperature, the silicon chip was slowly immersed into deionized water in a Langmuir–Blodgett trough, so as to form a self-assembly hexagonal close-packed ordered PS monolayer on the water surface. Then, dipped a substrate in the trough and then carefully pulled it out of the water surface where floating the PS film. Subsequently, the ordered hexagonal PS monolayer was transferred on the target substrate.

Fabrication Process of the MSMIM Absorber: In the first step, AIBS was used to deposit a 100 nm thick gold film on a cleaned silicon wafer, followed by immersing the substrate into a Langmuir–Blodgett trough to form ordered PS arrays on the surface of the gold film (as presented above). In the second step, a gold thin film (about 5 nm in thickness) was deposited on the top of the polymeric spheres to form MSM structure.Attributing to the restriction of vertical deposition technique, there formed a quasi-continuous gold film on the upper half of spheres, but there are almost no Au clusters appeared on the lower half surface of PS. Thus, PSs were assumed to be coated by a gold hemispherical shell on the top. In the third step, ALD was exploited to grow a smooth and conformal Al$_2$O$_3$ (10/30/50 nm) dielectric layer on the spherical surface. During the ALD process, trimethyl-aluminum (Al(CH$_3$)$_3$, TMA) reacted with H$_2$O to produce Al$_2$O$_3$ in vacuum chamber, which is an ideal strategy to grow conformal coatings on a 3D nanostructure surface. Finally, the other gold thin film was deposited by AIBS on the top to form the MSMIM plasmonic nanostructure.

Characterization and Measurements: The morphologies of the fabricated samples were characterized by SEM (FEI Sirion 200) operated at an accelerating voltage of 10 kV. The experimental reflection and transmission spectra were characterized using an FTIR spectrometer (Bruker IFS 66v/S), which is equipped with reflection module allowing for angles ranging from 13° to 80°. The measured reflection spectra are normalized with respect to a gold mirror. Since the bottom gold film is much thicker the penetration depth of light in the IR regime, the transmittance (T) of the structure is nearly zero. The absorbance (A) can thus be calculated as A = 1 − R.

Numerical Simulations: All electromagnetic wave numerical simulations were performed using finite-difference-time-domain (FDTD) method based commercial package (FDTD solutions, Numerical Inc.). In the simulations, the source with wavelength range of 0.8–10 µm was launched into FDTD simulation zone. Periodic boundary conditions were imposed along the x- and y-axes. Finer meshes sized in 1 nm were adopted to discretize the nanostructure where strong inhomogeneity exists. The complex dielectric constants of gold were extracted by ellipsometric measurements as presented in Figure S7 of the Supporting Information. The optical constants of Al$_2$O$_3$ are taken from the literature.² The electric permittivity of polystyrene spheres is taken as 2.25 over the wavelength range.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
This work was supported by the National Key R&D Program of China (2017YFA0205800), the National Natural Science Foundation of China (61471345), the Frontier Science Research Project (Key Programs) of Chinese Academy of Sciences under Grant No. QYZDJ-SSW-SLH018, the National Young 1000 Talent Plan, and the Shanghai Science and Technology Committee (16)C1403500.

Conflict of Interest
The authors declare no conflict of interest.

Keywords
broadband absorber, infrared atmospheric transparency window, large area, plasmonic metasurface, self-assembly technique

Received: May 19, 2019
Revised: June 21, 2019
Published online: July 25, 2019

[1] E. Hecht, Optics, 4th ed., Addison Wesley, New York, USA 2002.
[2] X. Gan, R. J. Shue, Y. Gao, I. Meric, T. F. Heinz, K. Shepard, J. Hone, S. Assefa, D. Englund, Nat. Photonics 2013, 7, 883.
[3] M. W. Knight, H. Sobhani, P. Nordlander, N. J. Halas, Science 2011, 332, 702.
[4] T. D. Dao, S. Ishii, T. Yokoyama, T. Sawada, R. P. Sugavaneshwar, K. Chen, Y. Wada, T. Nabatame, T. Nagao, ACS Photonics 2016, 3, 1271.
[5] B. Mulla, C. Sabah, Plasmonics 2016, 11, 1313.
[6] H. A. Atwater, A. Polman, Nat. Mater. 2010, 9, 205.
[7] Y. Chen, L. Wen, X. Hu, R. Xu, Q. Chen, Plasmonics 2018, 13, 1603.
[8] Y. Zhai, Y. Ma, S. N. David, D. Zhao, R. Lou, G. Tan, R. Yang, X. Yin, Science 2017, 355, 1062.
[9] M. M. Hossain, B. Jia, M. Gu, Adv. Opt. Mater. 2015, 3, 1047.
[10] K. T. Lee, S. Seo, L. J. Guo, Adv. Opt. Mater. 2015, 3, 347.
[11] T. Xu, Y. K. Wu, X. Luo, L. J. Guo, Nat. Commun. 2010, 1, 59.
[12] S. P. Mahulikar, H. R. Sonawane, G. Arvind Rao, Prog. Aerosp. Sci. 2007, 43, 218.
[13] J. C. Liu, Y. A. Liou, M. X. Wu, Y. J. Lee, C. H. Cheng, C. P. Kuei, R. M. Hong, IEEE Trans. Geosci. Remote Sens. 2015, 53, 1394.
[14] X. Xiong, C. L. Zou, X. F. Ren, G. C. Guo, IEEE Photonics Technol. Lett. 2014, 26, 1726.
[15] W. Li, U. Guler, N. Kinsey, G. V. Naik, A. Baltasseva, J. Guan, V. M. Shalaev, A. V. Kildishev, Adv. Mater. 2014, 26, 7959.
[16] Y. Xie, X. Fan, Y. Chen, J. D. Wilson, R. N. Simons, J. Q. Xiao, Sci. Rep. 2017, 7, 40490.
[17] J. T. Liu, N. H. Liu, J. Li, X. Jing Li, J. H. Huang, Appl. Phys. Lett. 2012, 101, 052104.
[18] S. K. Kim, K. D. Song, M. Qiu, Phys. Rev. Lett. 2014, 113, 1137.
[19] D. Zhao, L. Meng, H. Gong, Y. Chen, Y. Chen, M. Yan, Q. Li, M. Qiu, Appl. Phys. Lett. 2014, 104, 221107.
[20] T. López-Rios, D. Mendoza, F. J. García-Vidal, J. Sánchez-Dehesa, B. Pannietier, Phys. Rev. Lett. 1998, 81, 665.
[21] L. Meng, D. Zhao, Z. Ruan, Q. Li, Y. Yang, M. Qiu, Opt. Lett. 2014, 39, 1137.
[22] A. Tittl, A. K. Michel, M. Schaferling, X. Yin, B. Gholipour, L. Cui, M. Wuttig, T. Taubner, F. Neubrech, H. Giessen, Adv. Mater. 2015, 27, 4597.
[23] X. Pan, H. Xu, Y. Gao, Y. Zhang, L. Sun, D. Li, Z. Wen, S. Li, W. Yu, Z. Huang, J. Wang, B. Zhang, Y. Sun, J. Sun, X. Meng, X. Chen, B. Dagens, J. Hao, Y. Shen, N. Dai, J. Chu, Adv. Opt. Mater. 2018, 6, 1800337.
[24] Z. H. Jiang, S. Yun, F. Toor, D. H. Werner, T. S. Mayer, ACS Nano 2011, 5, 4641.
[25] Y. Cui, Y. He, Y. Jin, F. Ding, L. Yang, Y. Ye, S. Zhong, Y. Lin, S. He, Laser Photonics Rev. 2014, 8, 495.
[26] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, W. J. Padilla, Phys. Rev. Lett. 2008, 100, 207402.
[27] Y. Cui, K. H. Fung, J. Xu, H. Ma, Y. Jin, S. He, N. X. Fang, Nano Lett. 2012, 12, 1443.
[28] P. Bouchon, C. Koechlin, F. Pardo, R. Haïdar, J.-L. Pelouard, Opt. Lett. 2012, 37, 1038.
[29] D. Ji, H. Song, X. Zeng, H. Hu, K. Liu, N. Zhang, Q. Gan, Sci. Rep. 2015, 4, 4498.
[30] A. Cattoni, P. Ghenuche, A. M. Haghiri-Gosnet, D. Decanini, J. Chen, J. L. Pelouard, S. Collin, Nano Lett. 2011, 11, 3557.
[31] Z. Liu, P. Zhan, J. Chen, C. Tang, Z. Yan, Z. Chen, Z. Wang, Opt. Express 2013, 21, 3021.
[32] A. Moreau, C. Ciraci, J. J. Mock, R. T. Hill, Q. Wang, B. J. Wiley, A. Chilkoti, D. R. Smith, Nature 2012, 492, 86.
[33] G. M. Akselrod, J. Huang, T. B. Hoang, P. T. Bowen, L. Su, D. R. Smith, M. H. Mikkelsen, Adv. Mater. 2015, 27, 8028.
[34] M. J. Rozin, D. A. Rosen, T. J. Dill, A. R. Tao, Nat. Commun. 2015, 6, 7325.
[35] L. Zhou, Y. Tan, J. Wang, W. Xu, Y. Yuan, W. Cai, S. Zhu, J. Zhu, Nat. Photonics 2016, 10, 393.
[36] L. Zhou, Y. Tan, D. Ji, B. Zhu, P. Zhang, J. Xu, Q. Gan, Z. Yu, J. Zhu, Sci. Adv. 2016, 2, e1501227.
[37] X. Yu, L. Shi, D. Han, J. Zi, P. V. Braun, Adv. Funct. Mater. 2010, 20, 1910.
[38] J. Hao, J. Wang, X. Liu, W. J. Padilla, L. Zhou, M. Qiu, Appl. Phys. Lett. 2010, 96, 251104.
[39] C. Lumdee, B. Yun, P. G. Kik, ACS Photonics 2014, 1, 1224.
[40] J. Hao, L. Zhou, M. Qiu, Phys. Rev. B 2011, 83, 165107.
[41] J. Kischkat, S. Peters, B. Gruska, M. Semtsiv, M. Chashnikova, M. Klinkmüller, O. Fedosenko, M. Machulik, A. Aleksandrova, G. Monastyrskyi, Y. Flores, W. Ted Masselink, Appl. Opt. 2012, 51, 6789.