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Giant Broadband One Way Transmission Based on Directional Mie Scattering and Asymmetric Grating Diffraction Effects *

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High performance optical diode-like devices are highly desired in future practical nano-photonic devices with strong directional selectivity. We demonstrate a kind of giant broadband reciprocity optical diode-like devices by simultaneously using the directional Mie scattering effect and the asymmetric grating diffraction effect. The maximum asymmetric subtraction and the asymmetric transmission ratio can reach nearly 100% and 40 dB at specified wavelength, respectively. In a wide waveband from 500 nm to 800 nm, the asymmetric subtraction and the ratio keep larger than 80% and 3.5 dB, respectively, even under oblique incidence. To the best of our knowledge, this is the best one-way-transmission effect observed in the reciprocity optical diode-like devices. In addition, we further demonstrate that this one-way-transmission effect can bring an effective absorption enhancement on gold films. The giant, broadband and angle-insensitive one-way-transmission effect demonstrated here is far beyond the well-known anti-reflection effect in the light-trapping devices and will bring new design philosophy for nano-photonic devices.

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In recent years, optical diode-like devices (ODLDs) have attracted plenty of research interests since their significant potential applications in developing next-generation all-optical computing and processing devices and systems.[1–7] Both of the non-reciprocity and reciprocity schemes have been developed to achieve ODLDs. The non-reciprocity scheme usually utilizes high-order optical effects, such as magneto-optical effect,[2] optical nonlinearity,[8–11] indirect inter-band photonic transitions,[3,12,13] and optoacoustic effect,[14] to break the widely existed Lorentz symmetry.[15] Although the resulted non-reciprocity ODLDs own strict one-way-transmission (OWT) effect and can be used as opto-isolators, most of the current non-reciprocity methods suffer from the extremely low compatibility with complementary metal-oxide semiconductor (CMOS) process. The reciprocity scheme provides a loose route to achieve ODLDs, which tactfully bypasses the Lorentz restricted conditions by utilizing specific asymmetric optical mode conversion,[16] including diffraction mode,[17–20] polarization states of light,[21–23] and the spatial modes.[24,25] Compared with non-reciprocity ODLDs, reciprocity ODLDs can not only be realized without limitation to certain materials but also be compatible with CMOS fabrication process.

The reciprocity scheme greatly simplifies the realization conditions of ODLDs. However, it is still of challenge to achieve high performance ODLDs with high asymmetric transmission efficiency, wide response waveband and low sensitivity to the incident angle of light. Our previous work has proved that the asymmetric diffraction effect is an effective route to achieve broadband and high asymmetric transmission efficiency ODLDs.[17] In this work, we further employ the directional Mie scattering effect to improve the performance of diffraction-driven reciprocity ODLDs by exploring the optical properties of the nano-pyramid array on a high refractive index substrate (NPA-HRIS). In fact, the pyramid structure has been widely used as an impedance matching layer to reduce the light reflection from the object surface[26–33] or enhance the absorption of functional devices.[34–37] Especially for efficient light trapping in solar cells, it has been proved that in both theory and experiment, nano-pyramid arrays on surface of photovoltaic devices can greatly improve the external quantum efficiency.[34–36] Effective medium theory and impedance matching theory are usually used to explain why almost no light reflects from the pyramid structure modified surface.[28,38,39] In this work, we demonstrate the existence of an excellent OWT effect in our NPA-HRIS, which is far beyond the anti-reflection effect in improving the light-trapping effect in thin film solar cells, and cannot be explained by both of the impedance matching theory and the effective medium theory.

The designed NPA-HRIS is shown in Fig. 1(a).

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The bottom surface of pyramids is square with side length of P, and the height is set to be h. The dielectric pyramids and substrate are set as the same material with refractive index of n. To analyze the OWT effect in the nano-pyramid structure, a systematic numerical investigation is performed on the forward and backward transmission properties based on the finite-different time-domain (FDTD) method. The forward and backward illuminations are defined as light illuminated along the $-z$ and $+z$ directions, respectively. A periodic boundary condition is used in x and y directions, and a perfect match layer is used in z direction. An x-polarized plane wave with wavelengths from 350 nm to 850 nm is placed in reflection space to illuminate the HRIS-NPA. Electric field in both transmission and reflection sides are recorded to calculate the energy and diffraction efficient of different diffraction orders.

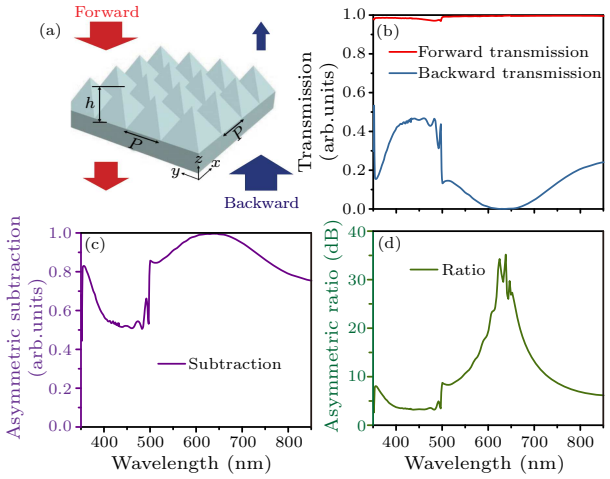

Fig. 1. (a) Schematic diagram of the designed NPA-HRIS. The red and blue arrows denote the forward ($-z$) and backward ($+z$) illumination directions; (b) simulated transmission spectra under forward (red) and backward (blue) illuminations. The asymmetric subtraction and the ratio calculated by these transmission spectra are shown in (c) and (d), respectively. The structure parameters are $P = 500$ nm, $h = 480$ nm, and $n = 2.59$.

An optimized result is shown in Figs. 1(b)–1(d), where the optimized parameters are $P = 500$ nm, $h = 480$ nm, and $n = 2.59$, respectively. A giant broadband OWT effect is observed, and the forward transmittance can reach above 97% in the entire visible band from 350 nm to 850 nm, while the backward transmittance is smaller than 20% in the waveband from 500 nm to 800 nm. The asymmetric transmission efficiency of an ODLD can be quantified by asymmetric subtraction and the ratio of forward and backward transmittances:

$$\text{Asymmetric subtraction} = T_{\text{forward}} - T_{\text{backward}}, \quad (1)$$

$$\text{Asymmetric ratio} = 10\log\left(T_{\text{forward}}/T_{\text{backward}}\right), \quad (2)$$

where T_{forward} and T_{backward} refer to forward and backward transmittances, respectively. Our optimized NPA-HRIS shows the asymmetric subtraction above 80% and asymmetric ratio about 3.5 dB in the waveband from 500 nm to 800 nm. Especially at about 640 nm, the maximum asymmetric subtraction and the ratio can reach about 100% and 40 dB, respectively. To the best of our knowledge, this is the best OWT effect that observed in the reciprocal ODLDs. This giant broadband OWT effect can not only effectively reduce the reflectance from the cone-like structure surface in a wide waveband, but also block the light to transmit back. We will demonstrate that this giant broadband OWT effect is beyond the widely known anti-reflection effect in the light-trapping fields, and will suggest new design philosophy for the nano-photonics devices.

To further illustrate the practicability of the OWT effect in the NPA-HRIS, we further investigate the angle-dependent OWT effect and the diffraction light transmission in the substrate. As shown in Fig. 2, the NPA-HRIS shows an excellent angle-insensitive OWT effect. The forward transmittance is always larger than 95% in the waveband from 350 nm to 850 nm when increasing the incident angle from 0° to 60°, while the backward transmittance almost keeps in a low value range at the same time. This results in large asymmetric subtraction (Fig. 2(c)) and asymmetric ratio (Fig. 2(d)). This excellent angle-insensitive OWT effect is also very rare in previously reported ODLDs and make the NPA-HRIS very competitive for practical applications. It should be noted that the substrate used in simulations is semi-infinite, and this is reasonable for applications in fibers, solar cells and so on. An independent device can also be achieved by applying the semi-sphere substrate or the impedance matching layer, as mentioned in our previous work.[15]

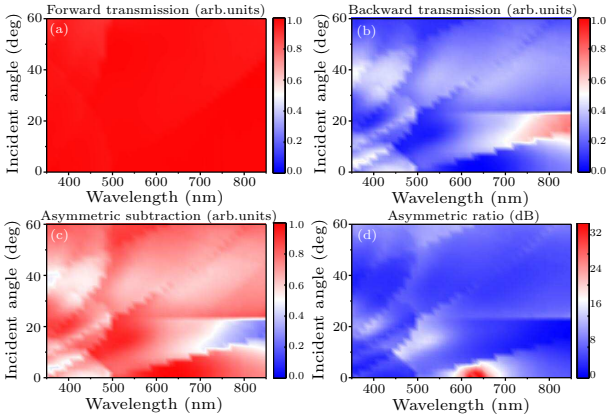

Fig. 2. Simulated forward (a) and backward (b) transmission spectra versus the incident angle; (c) and (d) the calculated asymmetric subtraction and ratio based on (a) and (b). The structure parameters are the same as those in Fig. 1.

The diffraction effect can be considered as the coherence stack of the scattering fields from every single pyramid in the NPA-HRIS. Thus, the scattering ef-

fect from single pyramid in the NPA-HRIS plays an important role on the resulted OWT effect. Before investigating the asymmetric diffraction effect of the NPA-HRIS, we investigate the directional Mie scattering effect of single nano-pyramid with and without the substrate.[40] The far-field scattering pattern of single nano-pyramid are calculated by projecting the scattering field of the nanopyramid to the far-field, where perfect match layers are used in every boundary in x, y and z directions and a total-field scattered-field linear light source is used to illuminate the nanopyramid. As shown in Figs. 3(a) and 3(b), when placed in a homogeneous medium, the single nano-pyramid shows a weak directional scattering effect, where most of the electromagnetic wave is scattered to the direction along the incident light. The weak directional scattering effect is attributed to the anisotropy of the nano-pyramid. However, this weak directional scattering effect can be greatly modified and enhanced by placing the nano-pyramid at the interface between two mediums with high refractive index difference. As shown in Figs. 3(c) and 3(d), when the nano-pyramid is placed on a substrate with refractive index of 2.59, most of the electromagnetic energy is scattered to the $-z$ direction, even when the incident light is along the $+z$ direction. It can be imagined that this directional scattering effect is very beneficial for trapping light in a desired field and enhancing electromagnetic field intensity.

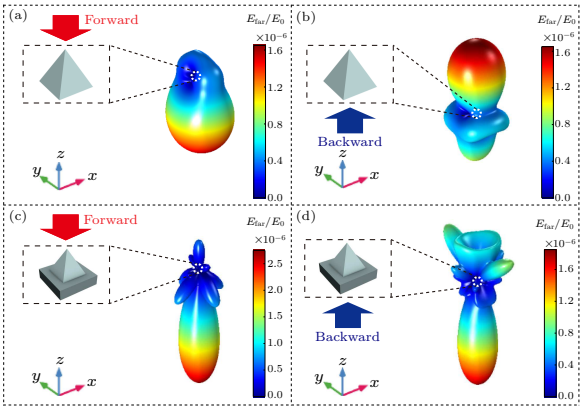

Fig. 3. The simulated far-field ($E_{\rm far}$) scattering pattern of single nano-pyramid in a homogeneous medium (a, b) and on a substrate (c, d) under forward (a, c) or backward (b, d) illuminations. The bottom surface of the nano-pyramid is a square with a side length of 500 nm. The height is 480 nm and the refractive index is 2.59. The investigated wavelength is 640 nm.

The directional Mie scattering effect will absolutely result in an asymmetric diffraction effect. To illustrate the influence of directional Mie scattering effect, we investigate the OWT effect of the nano-pyramid array without the substrate. As shown in Figs. 4(a) and 4(b), a weak and narrow-band OWT effect is only observed in the wavelength of smaller than the Wood–Rayleigh abnormity wavelength, i.e., 500 nm. The maximum asymmetric subtraction and the ratio are about 60% and 6 dB respectively. This OWT effect should be attributed to the influence from the geometrical anisotropy of pyramids, and is far smaller than that in the NPA-HRIS (Fig. 1), where the existed substrate changes the asymmetry of both the scattering effect from single pyramid and the diffraction effect from periodic pyramids. These results indicate the importance of the substrate in achieving an excellent OWT effect.

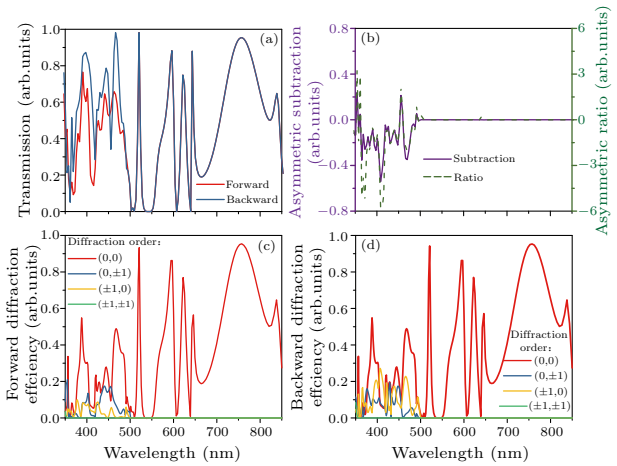

Fig. 4. (a) Simulated bidirectional transmission spectra of HRIS-NPA, and the related asymmetric subtraction and ratio are shown in (b), respectively. (c, d) The diffraction efficiency at different diffraction orders under forward and backward illumination respectively. The structure parameters are $P = 500$ nm, $h = 480$ nm, and $n = 2.59$.

As mentioned above, the asymmetric diffraction effect, i.e., diffraction efficiency difference in high orders, should be response for the giant broadband OWT effect in the NPA-HRIS. In fact, the diffraction effect is highly dependent on the grating period, microstructure, the refractive index n_1 in diffraction space, and so on, according to the vectorial diffraction theory.[41] For a specific diffraction order (m, n) in two-dimensional gratings under vertical illumination, the azimuth angle θ_{mn} and polar angle φ_{mn} can be simply calculated by

$$\theta_{mn} = \arcsin\left(\frac{\lambda}{n}\right)\sqrt{\left(\frac{m}{d_x}\right)^2 + \left(\frac{n}{d_y}\right)^2}, \tag{3}$$

$$\varphi_{mn} = \arctan\frac{nd_x}{md_y}, \tag{4}$$

where λ is the wavelength of incident light, n is the background refractive index in diffraction spaces, d_x and d_y are the lattice periods of gratings in x and y directions. The azimuth angle θ_{mn} should be located in a reasonable range from 0° to 90°. Thus, we have

$$0 < \lambda < n\left[\left(\frac{m}{dx}\right)^2 + \left(\frac{n}{dy}\right)^2\right]^{1/2}. \tag{5}$$

Equations (3) and (5) indicate that the diffraction order (m, n), azimuth angle θ_{mn} and polar angle φ_{mn}

are highly dependent on the background refractive index of n in diffraction space. For the NPA-HRIS investigated in this work, the transmission spaces under forward and backward illuminations own obviously different refractive indexes, i.e., $n_{\text{forward}} = 2.59$ and $n_{\text{backward}} = 1$, which will result in giant asymmetric diffraction effect, including asymmetric diffraction orders, angles and efficiency.

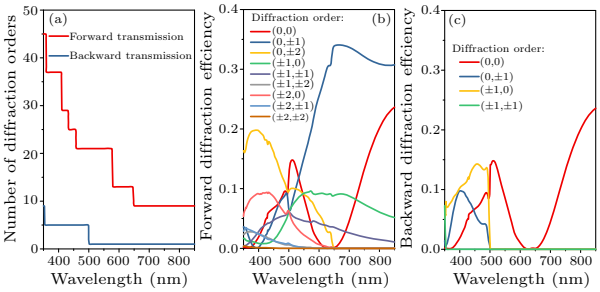

Fig. 5. (a) Total number of diffraction orders as a function of wavelength in transmission space under forward (red) and backward (blue) illuminations; (b, c) The diffraction efficiency at different diffraction orders under forward and backward illuminations. The structure parameters are the same as those in Fig. 2.

Figure 5 shows the simulated diffraction results of the NPA-HRIS with the parameters as the same as those used in Fig. 1. The total number of diffraction orders in forward transmission space is far larger than that in backward transmission space due to the high refractive index in forward transmission space, as shown in Fig. 5(a). The differences in the number of diffraction orders and diffraction angles between forward and backward transmissions indicate the existence of asymmetric diffraction effect in the NPA-HRIS. However, this cannot demonstrate the existence of the OWT effect in the NPA-HRIS, which is directly related to the difference in diffraction efficiency between forward and backward illuminations. Figures 2(b) and 2(c) show the diffraction spectra of all the existed diffraction orders. We can see that there exist 9 diffraction spectra with diffraction efficiency of larger than 0 in the forward transmission space, while in the backward transmission space, there exist only 4 diffraction spectra, which further reduces to one diffraction efficiency spectrum in the waveband of larger than 500 nm. In particular, a great diffraction efficiency difference is observed between the forward and backward diffractions, even for the same high diffraction orders, i.e. $(0, \pm 1)$, and should be attributed to the directional Mie scattering effect discussed above. These differences on diffraction efficiency result in a high transmittance difference between the forward and backward illuminations, and thus a giant broadband OWT effect.

Due to the limitation of Lorentz symmetry in the reciprocity ODLDs, the diffraction efficiency spectrum at $(0, 0)$ order in the forward transmission space is the same as that in the backward transmission space. Thus, a high diffraction efficiency at $(0, 0)$ order will weaken the transmittance difference and thus the OWT effect. Reducing or even eliminating the diffraction efficiency at $(0, 0)$ order is one of the basic targets in all of the diffraction-driven ODLDs. This basic target is achieved by employing the directional Mie scattering effect in this work. The diffraction efficiency at $(0, 0)$ order can be nearly eliminated completely at about 640 nm in the NPA-HRIS, which results in an extremely high asymmetric transmission ratio of about 40 dB. This is the highest asymmetric transmission ratio in the reported reciprocity ODLDs, indicating the great potential application prospect of the NPA-HRIS.

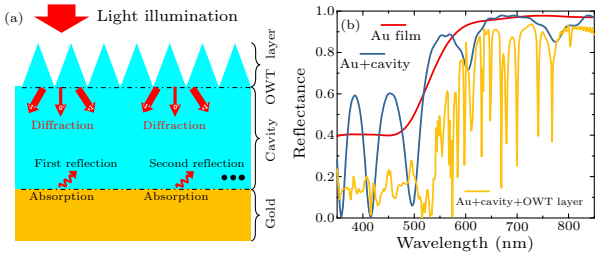

Fig. 6. (a) Schematic diagram of the NPA-HRIS placed on the gold film. The light illuminating from the top side will be trapped in the cavity layer by the OWT layer. (b) The reflectance spectra of the gold film (red), the gold film/ dielectric cavity (blue), and the OWT layer/dielectric cavity/gold film (yellow) as shown in (a).

The OWT effect owns a wide range of applications in nano-photonics. Here we firstly demonstrate the performance of the OWT effect in trapping lights. In order to effectively extract the real influence from the OWT effect, we employ a simple model to simulate the light absorption in a gold film modified by the NPA-HRIS. As shown in Fig. 6(a), this model consists of one OWT layer (i.e., NPA-HRIS), one dielectric layer with height of 500 nm, and one layer of gold film. It is obvious that the excellent OWT performance of the NPA-HRIS can let nearly 100% light go into the cavity at the initial illumination, and prevent the light to go out of the cavity, which finally results in high light-trapping efficiency. As shown in Fig. 6(b), when the gold film is covered with one layer of dielectric film, the reflectance located at some specified waveband is greatly reduced due to the Fabry–Perot cavity resonance. However, the total reflectance in the whole waveband does not decrease obviously. The average reflectance from the dielectric cavity covered gold film is about 0.7172, which is very close to that from the pure gold film (0.7574). However, when one OWT layer is covered on the top surface of the dielectric layer, the reflectance is obviously smaller than that of the gold film in the whole investigated waveband from 350 nm to 850 nm. The averaged reflectance decreases greatly to 0.5169, indicating the giant absorption enhancement from the OWT layer.

In conclusion, we have demonstrated a kind of gi-

ant, broadband and incident-angle-insensitive OWT effect in an NPA-HRIS by simultaneously introducing the directional Mie scattering effect and the asymmetric grating diffraction effect. The asymmetric subtraction and ratio can reach nearly 100% and 40 dB at specified wavelength, respectively, and keep larger than 80% and 7 dB in the waveband of 500 nm to 800 nm. This excellent OWT effect can also be kept unchanged for the incident angle from 0° to 60°. It is demonstrated that the OWT effect from the designed NPA-HRIS is an effective way to enhance the light-trapping ability, and is far beyond the well-known anti-reflection effect in the light-trapping devices. We believe that the giant, angle-independent and broadband OWT effect, will bring new design philosophy for nano-photonic devices.

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