AIP Applied Physics Letters

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Citation: Applied Physics Letters **105**, 201103 (2014); doi: 10.1063/1.4902162
View online: http://dx.doi.org/10.1063/1.4902162
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/105/20?ver=pdfcov
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Broadband diodelike asymmetric transmission of linearly polarized light in ultrathin hybrid metamaterial

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(Received 9 October 2014; accepted 8 November 2014; published online 19 November 2014)

We present the underlying theory, the design specifications, and the experimental demonstration of the broadband diodelike asymmetric transmission of linearly polarized light in the near-infrared regime. This result is achieved through the use of a two-layer hybrid metamaterial, composed of an L-shaped metallic particle and a double nano antenna. The experimental results are shown to agree well with the theoretical predictions and the simulated transmission spectra. The realization of the diodelike asymmetric transmission can be attributed to the combination of two independently functioning metallic structures, which are shown to perform their respective function even when shifted away from perfect alignment. This work offers a further step in developing broadband diodelike asymmetric transmission for use in electromagnetic devices. © *2014 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4902162]

Metamaterials are periodic artificial media with subwavelength unit-cell structure, and can exhibit unusual properties not found in nature.[1,2] Over the past decade, they have attracted significant attention since they promise to allow for the manipulation of light propagation to a seemingly arbitrary extent. Asymmetric transmission, which manifests itself as a difference in the total transmission between forward and backward propagations, has been an active field of research for quite some time, as it is exceedingly useful in constructing electromagnetic devices. Since the asymmetric transmission effect was proposed, it has been widely studied for differently polarized incident waves and their effect on metamaterial structures. In contrast to the nonreciprocal transmission achieved in magneto-optical, nonlinear, or time-dependent media,[3,4] the asymmetric transmission in metamaterials is reciprocal and fully compliant with Lorentz's reciprocity theorem. Asymmetric transmission of circularly and linearly polarized waves has been demonstrated by planar chiral[5–8] and three-dimensional metamaterials,[9–11] respectively. Furthermore, many devices have been designed to enhance the asymmetric transmission effect. Two kinds of bi-layered chiral metamaterials have been proposed to enhance the asymmetric transmission effects for circularly polarized waves.[12] Ultrathin chiral metamaterial slabs and multilayered metallic structures have been proposed for highly asymmetric and broadband transmission of linearly polarized waves.[13–15]

Recently, the diodelike asymmetric transmission effect for metamaterials has attracted growing attention in the scientific community for its possible applications in polarization transformers, diodelike devices, ultrafast information processing, and optical interconnects.[14–19] Mutlu *et al*. proposed a dual-band diodelike asymmetric transmission of linearly polarized, normally incident waves by designing a three-layer structure made of isotropic and linear materials.[11] Shi *et al*. further demonstrated a broadband diodelike asymmetric transmission by Babinet-inverted metasurfaces constructed by an array of asymmetrical split ring apertures.[18] However, these designs, which work in the GHz domain, have complicated structural parameters, and the diodelike asymmetric transmission strongly depends on the chirality or the strong coupling between the structures. Therefore, these devices require highly advanced fabrication techniques, which makes them difficult to implement in high-efficiency diodelike asymmetric transmission devices in the near-infrared and visible domain. A device utilizing a conventional half-wave plate and a polarizer can also produce a broadband asymmetric transmission for linear polarization. However, there exist some inherent disadvantages in the size and collimation of this optical system. In contrast, metamaterials enable us to design and achieve unprecedented broadband asymmetric transmission at the nanoscale, with a high level of integration and control of the working waveband.

In this letter, we present the underlying theory, the design specifications, and the experimental demonstration of a device for broadband diodelike asymmetric transmission of linearly polarized light in the near-infrared regime by combining two independently functioning metallic structures into an ultrathin two-layer hybrid metamaterial. The broadband diodelike asymmetric transmission can reach a bandwidth of 400 nm in virtue of its design, which incorporates a two-layer structure composed of an L-shaped metallic particle and a double nano antenna. The experimental results further verify the theoretical predictions and agree well with the simulated transmission spectra. Moreover, we demonstrate that the proposed hybrid metamaterial does not require critical alignment between the layers.

Let us first consider the theoretical analysis for the asymmetric transmission of linearly polarized light. Asymmetric

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transmission of linearly polarized light is usually caused by the partial polarization conversion of the incident light into the opposite polarization, which is asymmetric between the opposite directions of propagation. The transmission of coherent light through any dispersive optical system can be described by means of complex Jones matrices T.[9] We consider an incoming plane wave propagating along the $+z$-direction, with electric field as

$$E_i(r,t) = \begin{pmatrix} I_x \\ I_y \end{pmatrix} e^{i(kz-\omega t)}, \tag{1}$$

where ω, k, I_x, and I_y represent the frequency, wave vector, and complex amplitudes, respectively. The transmitted field is then given by

$$E_t(r,t) = \begin{pmatrix} T_x \\ T_y \end{pmatrix} e^{i(kz-\omega t)}. \tag{2}$$

The T matrix relates the generally complex amplitudes of the incident field to the complex amplitudes of the transmitted field

$$\begin{pmatrix} T_x \\ T_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} I_x \\ I_y \end{pmatrix} = T^{\text{Forward}} \begin{pmatrix} I_x \\ I_y \end{pmatrix}. \tag{3}$$

The superscript "forward" indicates the forward propagation (along $+z$-direction). If the medium does not contain magneto-optical material, the reciprocity theorem can be applied and the transmission matrix T^{Backward} for propagation in the backward direction (along-z-direction) can be written as

$$T^{\text{Backward}} = \begin{pmatrix} T_{xx} & -T_{yx} \\ -T_{xy} & T_{yy} \end{pmatrix}. \tag{4}$$

Furthermore, the transmittances in the two opposite propagation directions for x-polarization can be written as

$$t^{\text{Forward}} = |T_{xx}|^2 + |T_{yx}|^2, \tag{5a}$$

$$t^{\text{Backward}} = |T_{xx}|^2 + |T_{xy}|^2. \tag{5b}$$

In order to obtain the diodelike asymmetric transmission for linear x-polarization, the transmission matrix elements should satisfy the following conditions:

$$|T_{xx}| = 0, \tag{6a}$$

$$|T_{yx}|^2 = 0, \quad |T_{xy}|^2 = k(f) \quad \text{or} \quad |T_{yx}|^2 = k(f), \quad |T_{xy}|^2 = 0. \tag{6b}$$

$k(f)$ depends on the frequency of the incident light. Thereby, broadband diodelike asymmetric transmission can be achieved by setting $k(f)$ as a constant. This condition can be realized by the combination of structures with specifically tailored T matrices.

Based on the above considerations, we have constructed a two-layer hybrid metamaterial, as shown in Fig. 1(a). The first layer comprises a double nano antenna, while the second layer comprises an L-shaped metallic particle. Both layers are deposited into silicon dioxide. The samples were

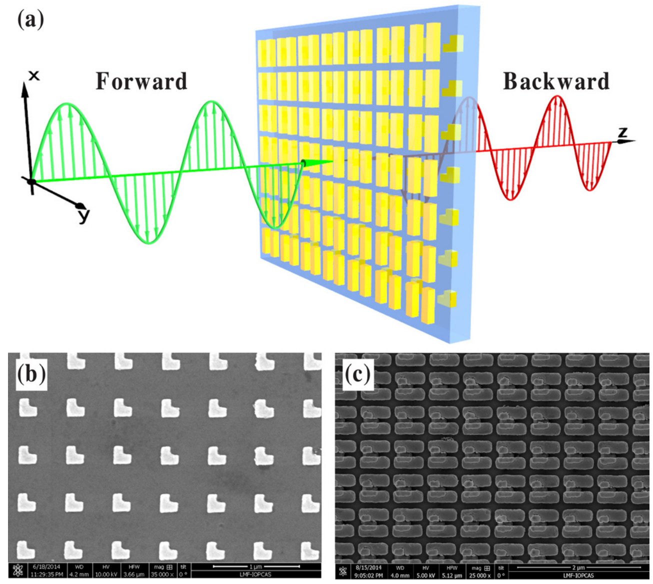

FIG. 1. (a) Schematics of the proposed two-layer hybrid metamaterial for x-polarized propagation in the forward and backward directions. (b) Scanning electron microscopy (SEM) image of the L-shaped metallic particle and (c) the double nano antenna.

fabricated by electron-beam lithography, evaporation deposition of gold, and plasma-enhanced chemical vapor deposition (PECVD) of silicon dioxide with the sample scanning electron microscopy (SEM) images presented in Figs. 1(b) and 1(c). A 50 nm layer of ITO was coated onto a quartz substrate as a charge releaser. A 200 nm thick polymethylmethacrylate (PMMA) resist was then spin-coated onto the substrate. The pattern was exposed using an electron-beam lithography system (JBX6300FS) at 100 keV. After exposure, the sample was developed in methyl isobutyl ketone: isopropyl alcohol (MIBK:IPA) (1:3) for 40 s and IPA for 30 s and then blown dry using pure nitrogen. A 2 nm chromium as adhesive layer and a 50 nm gold were deposited by thermal evaporation method. The pattern was transferred onto the substrate by a lithography process. After the PMMA resist was removed with acetone, a 50 nm thick SiO_2 layer was deposited onto the sample using PECVD. The pattern on a second Au layer (also with a thickness of 50 nm) was prepared by repeating the lithography processes. Finally, a 50 nm thick SiO_2 layer was deposited on top of the sample using PECVD.

The double nano antenna designed 450 nm in length (L_1) and 160 nm in width (W_1), while the distance between the two components of the double nano antenna was $D = 100$ nm. The L-shaped metallic particle designed 200 nm in length (L_2) and 100 nm in width (W_2). The periods of the two-layer unit-cell were all $P = 550$ nm in the x- and y-directions. To demonstrate the weak mutual influence between the two layers of the metallic structure, we fabricated three samples with different relative positions for the two layers: these represented a 0 nm and a 30 nm shift in the x-direction, and a 30 nm shift in the y-direction.

The optimized structure was achieved by using the CST Microwave Studio.[20] The refractive index of the quartz substrate is 1.47. The dielectric function of gold is defined by Drude mode with plasmon frequency $\omega_p = 1.37 \times 10^{16}\ \text{s}^{-1}$

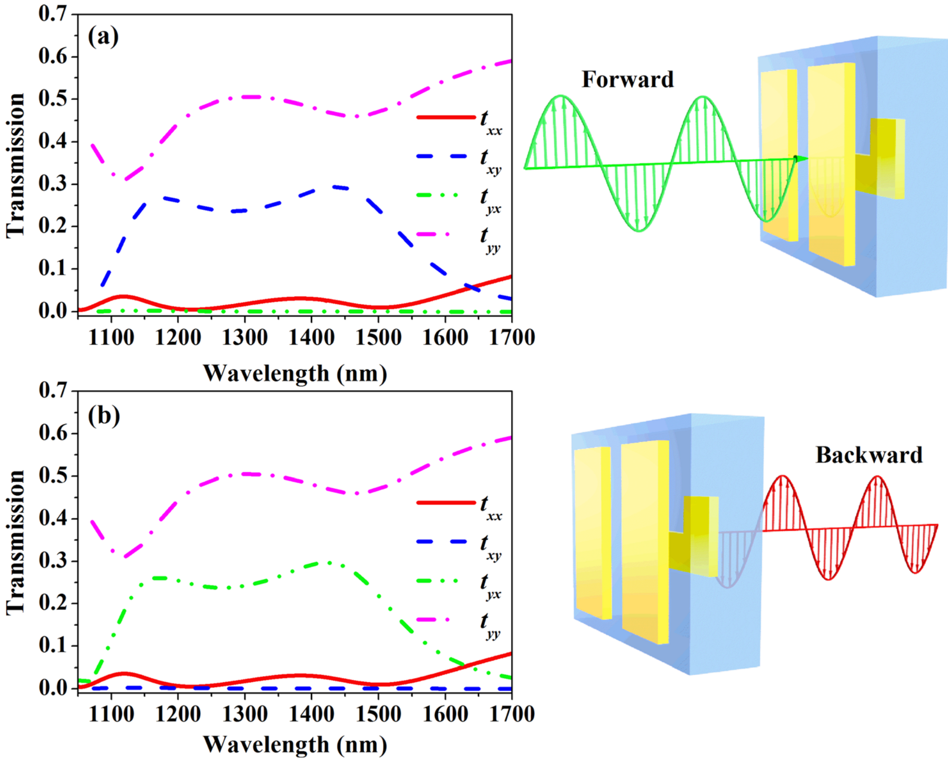

FIG. 2. Calculated squared moduli of four transmission matrix elements of the ultrathin hybrid metamaterial for x-polarized propagation in (a) the forward and (b) the backward directions.

and damping constant $\gamma = 4.08 \times 10^{13}\ \mathrm{s}^{-1}$.[21] To account for surface scattering, grain boundary effects in the thin gold film and inhomogeneous broadening, we used a damping constant three times higher than that used for bulk.[22,23] Periodic boundary conditions were used in the x- and y-directions. Perfectly matched layers are placed in the z direction to completely absorb the waves leaving the simulation domain in the direction of propagation. The excitation source was an x-polarized plane wave. The experiments were carried out through the use of a custom-built optical setting. Polarized white light from a bromine tungsten lamp illuminated the sample from the normal direction. Optical transmission with forward and backward incident waves was collected by an optical spectrum analyzer via a fiber coupler. By rotating the sample 180°, we were able to obtain the transmittance for the two opposite incident directions.

Figure 2 shows the calculated squared moduli, $t_{ij} = |T_{ij}|^2$, of four transmission matrix elements of the structure for x-polarized propagation in the forward and backward directions. For the forward-propagating wave, t_{xx} and t_{yx} are zero, and t_{xy} is nearly constant between 1200 nm and 1500 nm. For the backward-propagating wave, t_{xx} and t_{xy} are zero, and t_{yx} is nearly constant in the same spectral range. The simulated results agree well with the theoretical analysis across a broadband wavelength range. Menzel *et al.* proposed L-shaped and striped particles to achieve a broadband asymmetric transmission for circular polarized light in the near-infrared,[9] which is mainly caused by three-dimensional chirality and complex resonances between the L-shaped and striped particles. The proposed diodelike asymmetric transmission of linearly polarized light is formed by the partial polarization conversion of the incident light into the opposite polarization. The L-shaped metallic particle is used as a partial polarization converter, which is symmetric with respect to the opposite propagation directions. However, the reflection of the double nano antenna is polarization-dependent, which will completely reflect x-polarized waves.[24,25] Therefore, the transmission matrix elements t_{xx} and t_{yx} are zero, but t_{xy} is non-zero for forward propagation. According to Eq. (6), this leads to diodelike asymmetric transmission for linear polarization. Furthermore,

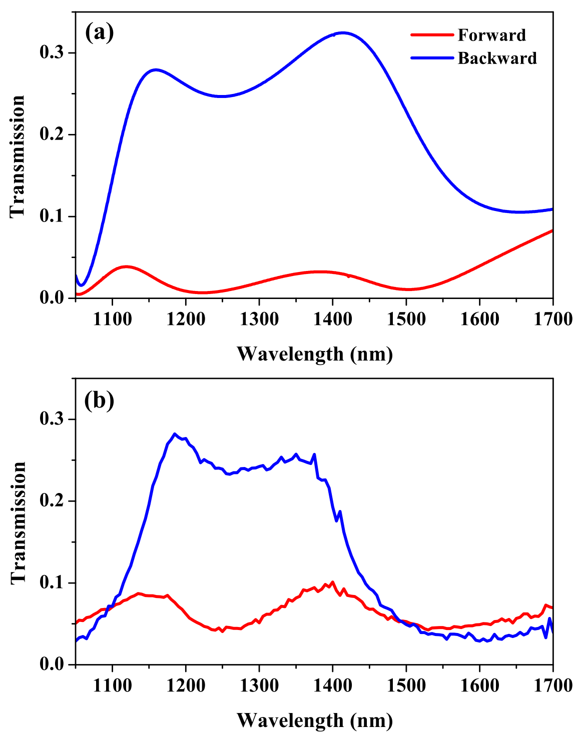

FIG. 3. (a) Simulated and (b) experimental transmission spectra of the ultrathin hybrid metamaterial for x-polarized wave propagating along the forward and backward directions.

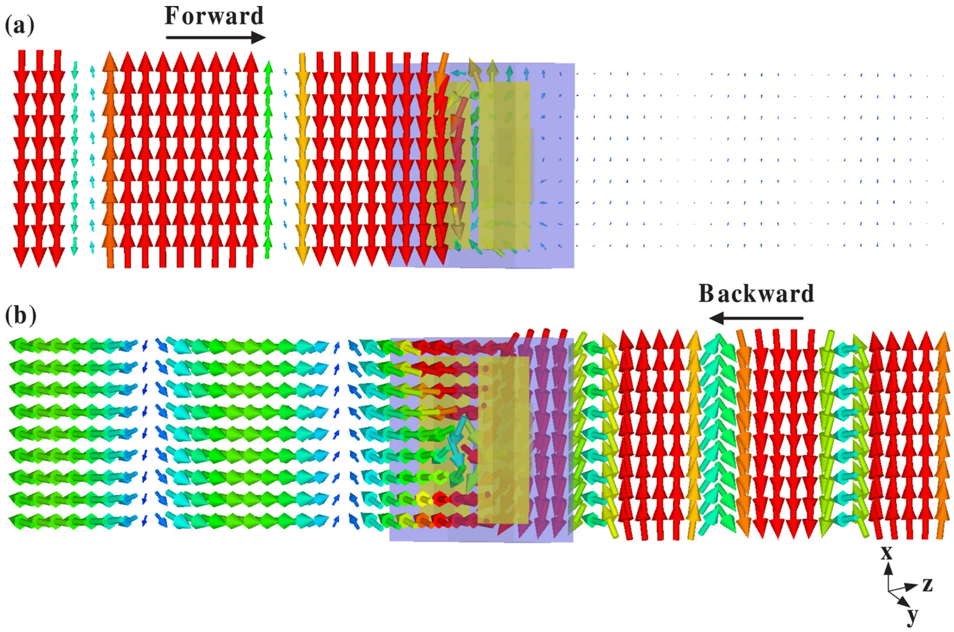

FIG. 4. Calculated electric field distributions at 1300 nm wavelength for an x-polarized wave incident along (a) the forward and (b) the backward directions.

no diodelike asymmetric transmission will be observed for the y-polarized wave because t_{yy} is non-zero. In addition, Fig. 2 shows that the cross-polarization components t_{xy} and t_{yx} can interchange with each other when the propagation direction is reversed.

To further demonstrate broadband diodelike asymmetric transmission, we give the simulated transmission spectra of our proposed ultrathin hybrid metamaterial for an x-polarized wave propagating along the forward and backward directions in Fig. 3(a). A strong diodelike asymmetric transmission from 1100 nm to 1500 nm is observed and achieves transmission values up to 30%. The experimentally obtained transmission spectra for x-polarized waves propagating along the forward and backward directions are shown in Fig. 3(b). An apparent broadband diodelike asymmetric transmission is obtained, which is in reasonable agreement with the simulated results. The bandwidth of the diodelike asymmetric transmission is slightly different between the experimental and simulated results due to the inaccuracy of the width of the fabricated L-shape. The right resonant peak is not apparent, as it is very sensitive to the width of the L-shape. In order to intuitively show the diodelike asymmetric transmission, the electric field distribution at 1300 nm wavelength for an x-polarized incident wave along the forward and backward directions is illustrated by simulation, as shown in Fig. 4. There is almost no electric field existing in the $+z$ area for forward propagation. On the other hand, along the opposite direction, the electric field exists in all areas. It is obvious that the results verify the theoretical predictions and agree well with the simulated transmission spectra.

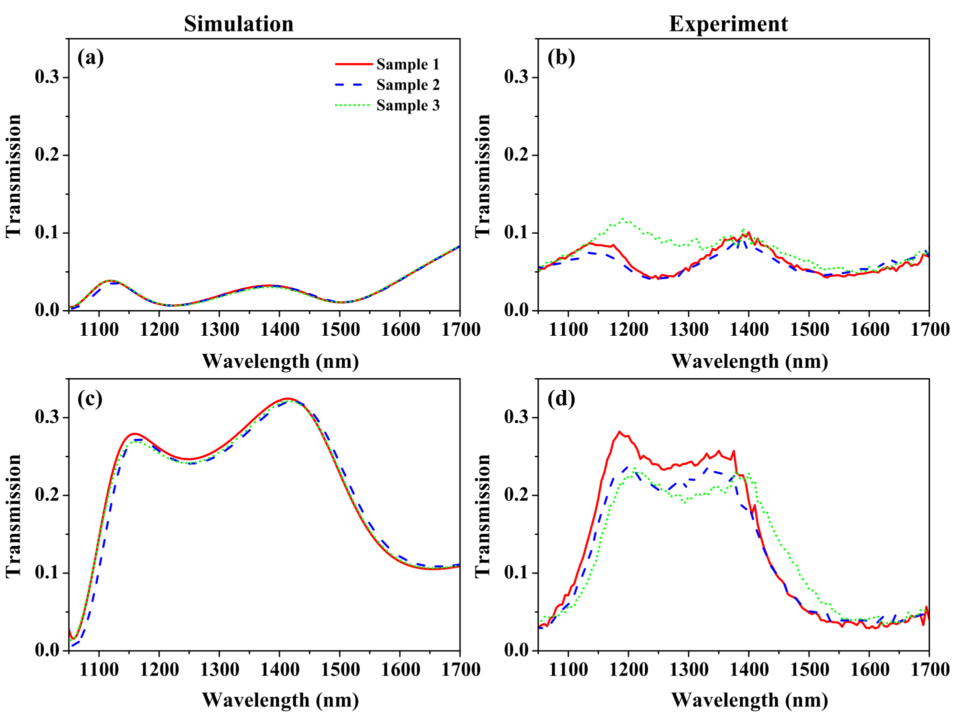

FIG. 5. (a) and (c) Simulated and (b) and (d) experimental transmission spectra of three relative translations for an x-polarized wave propagating along (a) and (b) the forward and (c) and (d) backward directions. Sample 1: the centers of the L-shaped metallic particle and the double nano antenna are aligned with each other; samples 2 and 3: the center of the L-shaped metallic particle has a 30 nm shift in x- and y-direction with that of the double nano antenna, respectively.

Using the theoretical predictions above, the L-shaped metallic particle can be treated as partial polarization converter, while the double nano antenna can be treated as selectively transmitting the converted polarization light. In essence, this means that the two metallic structures can be treated as two independently functioning components. In order to verify the weak mutual influence between the two layered metallic structures, we fabricated three samples with different relative positions for the components in each layer: both a 0 nm and a 30 nm shift in the x-direction, and a 30 nm shift in the y-direction. Figures 5(a) and 5(c) show the simulated transmission spectra of three relative translations for an x-polarized wave propagating along the forward and backward directions, respectively. Results show that the relative translations of the two structures have almost no influence on the broadband diodelike asymmetric transmission. The corresponding experimental transmission spectra in Figs. 5(b) and 5(d) also further confirm this conclusion, which agrees qualitatively with the simulated results. This characteristic will be beneficial to the real applications of the broadband diodelike asymmetric transmission effect.

In conclusion, we reported on the experimental observation and theoretical analysis of broadband diodelike asymmetric transmission for linearly polarized incident light in the near-infrared regime. Theoretical analysis shows that the broadband diodelike asymmetric transmission can be realized by combining two functional metallic structures into an ultrathin hybrid metamaterial. To verify the theoretical predictions, proof-of-concept examples of a hybrid metamaterial were fabricated, which were composed of an L-shaped metallic particle and a double nano antenna. The experimental results confirmed the broadband diodelike asymmetric transmission of linear polarization along the opposite propagation directions. In particular, the physical mechanism of this hybrid metamaterial requires minimal sophistication as regards fabrication technology, which is quite beneficial to its potential applications in compact and lightweight directional-electromagnetic devices. This result offers helpful insight, and provides intriguing possibilities to the design of devices based on broadband diodelike asymmetric transmission.

This work was supported by the National Basic Research Program (973 Program) of China (2012CB921900), the Chinese National Key Basic Research Special Fund (2011CB922003), the Natural Science Foundation of China (Nos. 61378006, 11304163, 11174362, and 91323304), the Program for New Century Excellent Talents in University (NCET-13-0294), the Knowledge Innovation Project of CAS (Grant No. KJCX2-EW-W02), the Natural Science Foundation of Tianjin (13JCQNJC01900), The National Science Fund for Talent Training in Basic Sciences (J1103208), and the 111 Project (B07013).

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