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Asymmetric radiation transfer based on linear light-matter interaction

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ABSTRACT

In this paper, asymmetric radiation transfer based on linear light-matter interaction has been proposed. Two naturally different numerical methods, finite difference time domain (FDTD) and rigorous coupled wave analysis (RCWA), are utilized to verify that asymmetric radiation transfer can exist for linear plasmonic meta-material. The overall asymmetry has been introduced to evaluate bifacial transmission. Physics for the asymmetric optical responses have been understood via electromagnetic field distributions. Dispersion relation for surface plasmon polariton (SPP) and temporal coupled mode theory (TCMT) have been employed to verify the physics discussed in the paper. Geometric effects and the disappearing of asymmetric transmission have also been investigated. The results gained herein broaden the cognition of linear optical system, facilitate the design of novel energy harvesting device.

1. Introduction

Totally asymmetric radiation transfer devices may allow the light to follow in one direction and block it in the opposite direction [1,2]. System which can allow asymmetric radiation transfer can find various application points, from fast optical signal processing and communication [3], energy harvesting to thermal radiation control [4–6]. Most recently, Yakir et al. by involving time-dependent refractive index, have proposed the asymmetry of emission and absorption can further improve the performance of energy harvesting system [7]. They have built a novel antenna which has different responses to the incident and emitting electromagnetic wave in the GHz region and proposed the similar method can be translated to infrared region.

To generate asymmetric radiation transfer is inherently difficult due to time-reversal symmetry of light-matter interaction [8]. Various configurations based on optical non-reciprocity have been suggested to generate asymmetric response, including optical isolator based on Faraday effects [9–11], application of nonlinear material [3,12], device with time-dependent refractive index mentioned above [13,14] and so on. Rapid development of meta-materials has also provided novel method to manipulate optical response, like nano-sandwich [15], metaweaves [16], and so on. In this paper, method to generate asymmetric radiation transfer based on linear light-matter interaction and the physics behind it have been proposed. The nanostructure proposed in this paper is one-dimensional grating, even with unidimensional structure, the nanostructure has asymmetric optical responses for both transverse magnetic (TM) and transverse electric (TE) polarized waves. The role such kind of meta-material plays in thermal radiation is to manage the radiation flux in the system. In an asymmetric radiation transfer system, optical response of structure varies greatly with different direction of incidence and propagation [17]. For traditional optical elements, two counter-propagating waves inside the material behave similarly. With the free of this limitation, some novel devices can be proposed. For example, in a solar thermophotovoltaic system, the conversion efficiency is dependent on the area ratio of absorber/emitter. With fixed area ratio, conversion efficiency cannot be changed. But if one can place an asymmetric element in the system, it can break the balance of radiation exchange, providing new possibility to further improve the conversion efficiency.

The paper is arranged as follows: first, asymmetric radiation transfer in a linear meta-material has been discussed and its physical meaning has been verified. Second, TE/TM polarization and forward/ backward incidence transmission spectrum are obtained. We investigate near field light distributions to demonstrate the mechanism of asymmetric optical response. Disappearance of asymmetric radiation transfer has been discussed. Two multipole modes are distinguished to understand the physical origin of asymmetric effect. Furthermore, Fano resonance induced by the interference between the narrowband SPP and the broadband multipole modes is discussed in this paper. Dispersion relation and TCMT are employed to understand physics within the asymmetric spectral response. Geometric effects are also discussed, forward& backward

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transmission spectrum for TM wave are calculated to indicate the accuracy of the numerical method.

2. Physical meaning of asymmetric radiation transfer in linear light-matter interaction

To begin with, the most pivotal question the author should answer is whether asymmetric radiation transfer can exist in a linear meta-material? The answer is yes. As being pointed out by Jalas et al. [1], magneto-optical material, nonlinear light-matter interaction and time-variant refractive index can generate optical nonreciprocity, as known by vast majority of scientific community. Beyond non-reciprocal devices aforementioned, asymmetric optical responses can also exist for linear meta-material. In 2014, Mazor et al. [16] have pointed out that metaweaves consisting of planar one-way nanoscale plasmonic particles chains can generate strong asymmetric response. The next question is how can one study asymmetric radiation transfer. Basically, the scattering matrix of a device should be asymmetric if its optical response is asymmetric. If one studies a device with only two ports, it means $S_{21}{\neq}S_{12}$ [1]. Scattering parameters are complex valued matrices describing the transmission and reflection of electromagnetic waves at different ports, and asymmetry of scattering matrix for a 2 ports device means the voltage transmission coefficient from port 1 to 2 and from port 2 to 1, are not equal. Previous publications like [18,19] have defined the scattering matrix of a slab material. As illustrated in Fig. 1(a), the slab material is seen as a junction between single-mode waveguides supporting propagation of plane wave in a wide spectral region, and the 2 semi-infinite spaces separated by the material are seen as the 2 ports. With the alternation of exciting and receiving between 2 ports, one can obtain all the elements in scattering matrix. Particularly for a planar material in free space, the scattering matrix can be seen as the optical responses with excitation sources in the different sides, which means $|S_{21}|^2{=}\tau_{\mathrm{Forward}}$, $|S_{12}|^2{=}\tau_{\mathrm{Backward}}$. Also, the reflection efficiencies from the two sides will also be unequal if the structure is asymmetric in geometry, as experimented by Shevchenko et al. [15].

Before detailed discussion of asymmetric radiation transfer, two different numerical methods are deployed on free standing 2D periodic Ag triangle array, as FDTD and RCWA. Those two methods are different in nature, and later it will be shown the results are similar. In this way, one can see the credibility of asymmetric transmission. A free standing periodic Ag triangle array with $w = 1.2\,\mu\mathrm{m}$, $P = 1.6\,\mu\mathrm{m}$, $h = 2\,\mu\mathrm{m}$ has been utilized to verify the asymmetric radiation transfer and numerical convergence. All optical constants in this work are obtained from Palik's book [20]. In this paper, the forward transmission is defined as the transmission ratio of light illuminated to the vertices of the structure, and the backward transmission is obtained by illuminating light to the bottom of the structure, as illustrated in Fig. 1(a). In FDTD method, as shown in Fig. 1(b), the region is divided into square meshes [21]. Two lines of meshes located at different sides of the material are chosen as the two ports, scattering parameters can be obtained by alternating the exciting/receiving modes of two ports. When one chooses port 1 as the exciting source, by calculating the time-average power flux in the port 2, one can obtain the spectral forward transmission for TE and TM polarized waves. By alternating port 2 as the source, the spectral backward transmission ratio can be obtained as well. In the RCWA utilized for calculation as shown in Fig. 1(c), monochromatic transmission wave can be written as $E_t = \Sigma t_{\lambda i}\ \exp[-i(k_{x,i}x\ \text{-}\ k_{z,i}z)]$ for transverse electric (TE) wave and $H_t = \Sigma t_{\lambda i}\ \exp[-i(k_{x,i}x\ \text{-}\ k_{z,i}z)]$ for transverse magnetic (TM) wave, with the total transmission efficiencies $t_\lambda = \Sigma t_{\lambda i} t_{\lambda i}{}^{*} Re(k_{z,i}\ /\ k_{z0})$. Wherein $t_{\lambda i}$ is the transmission factor to certain order of diffracted wave, $k_{x,i} = 2\pi i/P$ and $k_{z,i}$ are the wavevectors for the diffracted wave in x and z axis, k_{z0} is the incident wavevector along z axis [22]. To obtain the spectral transmission of slanted strips, the structure has been divided into discrete layers, whose widths gradually change from top to bottom. With the width of discrete layer gradually increases, the forward transmittance has been obtained. To calculate the backward transmittance, the discrete layers need to be arranged in the opposite order. 4 combinations of diffraction orders and number of discrete layers have been chosen for RCWA, as 50 order multiplies 10 layer, 50 order multiplies 20 layer, 50 order multiplies 30 layer and 100 order multiplies 30 layer. The computation times spent for RCWA have been shown in Table 1. As can be seen in Fig. 1(d), at 50 order multiplies 10 layer and 50 order multiplies 20 layer, there exists discrepancy. When using 50 order multiplies 30 layer and 100 order multiplies 30 layer, the spectral transmittances converge to a fixed curve, and no discrepancy can be seen. As employing 50 order multiplies 30 layer can reduce the computation time considerably comparing 100 order multiplies 30 layer, we choose 50 order multiplies 30 layer for calculation. For FDTD, square mesh with 1 nm, 3 nm and 7 nm have been used for computation. It can be seen in Fig. 1(d), the discrepancy for FDTD method can almost be neglected, indicating a convergence of numerical calculation. While for RCWA method, with the increase of diffraction order and discrete layers, the discrepancy reduce. For 50 order multiplies 30 layer and 100 order multiplies 30 layer, the discrepancy is negligible. Numerical convergence has been achieved. Considering the computation time shown in Table 2, 3 nm square mesh has been chosen. It can be seen even FDTD and RCWA are totally different numerical methods, but the spectral optical responses are generally same. Besides, the values of forward transmittances are generally larger than the backward cases. To further indicate the numerical convergence, transmission at 0.8 μm are selected for specific discussion. This is because for the TE polarized wave, a transmission peak locates there, while for the TM polarized wave, there is a transmission valley. As shown in Tables 3 and 4, the discrepancies for monochromatic wave transmission generally disappear as discussed above, showing accuracy of numerical method. In specific spectral region $|S_{21}|^2 = \tau_{Forward} \neq |S_{12}|^2 = \tau_{Backward}$, asymmetric radiation transfer has been achieved.

Table 1
Computation time for RCWA.

Diffraction order / layer number	50/10	50/20	50/30	100/30
Backward, TE&TM	58s	123s	181s	870s
Forward, TE&TM	57s	121s	186s	854s

As an analogy to the asymmetric electron flow in the electronic diode, a meta-material junction made of dissimilar material has been studied. The junction designed in this study is illustrated in Fig. 2(a), semi-infinite Si and SiO$_2$ substrates are separated by a 1D grating with ridges consisted of Ag and Au nanostrips. The slanted angle of ridges is defined as θ, the thickness of Ag and Au layer are defined as h_1 and $h_{2,}$ in this paper there is always $h_1 = h_{2,}$ and the overall height $h = (h_1 + h_2)$. The period of grating is P, the width of base is w_2 for Au nanostrips and w_1 for Ag top margin. One can obtain $\theta = \arctan\,[(w_1 + w_2)/h]$. With dissimilar material for grating and substrates, this structure can better elucidate the physics for asymmetric radiation transfer than homogenous structure. For asymmetric structure made of homogenous material, asymmetric radiation transfer exists like the free-standing Ag arrays we discussed, but the responses curves are quite approached like [15]. Also, the light distributes in a more similar way in near-field with two opposite incident waves in the homogenous structure. In this paper, by taking the advantages of dissimilar materials, we can better demonstrate the physics for the asymmetric effect.