Abstract  We theoretically demonstrate direction-dependent polarization conversion efficiency, yielding unidirectional light transmission, through a two-layer nanostructure by using the angular spectrum representation of optical near-fields. The direction-dependent efficiency is characterized based on the momentum of near-field light, which is much larger than that of propagating light. The theory provides results that are consistent with electromagnetic numerical simulations. This study offers a design principle for metamaterials in realizing optical properties, such as the unidirectionality observed here.

Unidirectional light propagation has been intensively studied because of its crucial importance in practical optical systems, such as to achieve one-way signal transfer or avoid back-reflections [1]. The Faraday effect is the most well-known example, and this effect is used in a variety of device architectures. By using isotropic materials, a one-way diffraction [2] and unidirectional light transmission has been shown [3]. Asymmetric transmission of linearly or circularly polarized light by optical metamaterials has also been demonstrated [4]. Regarding isotropic-material-based nanostructures that exhibit unidirectional/asymmetric light transmission [3,4], a common feature is that they contain subwavelength-scale three-dimensional architectures, typically consisting of two-layer structures. Interactions among nanostructured two-layer systems yield interesting optical properties. Nevertheless, the physical reasoning and formalism have been limited to the notion of far-field optics. The coupling of surface plasmon polaritons has been postulated as the elemental physical process; however, a detailed formalism concerning near-field processes and unidirectional transmission has not been investigated yet.

Here we present a rigorous theoretical foundation for characterizing unidirectional signal transfer in two-layer nanostructured matter based on the angular spectrum representation of optical near-fields. The evanescent wave is the most remarkable manifestation of optical near-fields that propagate parallel to the boundary surface and exhibit an exponential decay in the direction normal to the surface [5,6]. In the near-field regime, the angular spectrum of the scattered fields involves evanescent waves with wavevectors (or momentum) along the surface much larger than that of optical wave in free space.
What we particularly address in this paper is to theoretically and numerically demonstrate that the polarization conversion efficiency from $x$-polarized input light to $y$-polarized output light in the forward direction differs from the polarization conversion efficiency from $y$-polarization input to $x$-polarization output in the backward direction through a two-layer planar nanostructure. By considering the polarization conversion in the forward and backward directions as the transfer of near-field light momentum based on the angular spectrum theory, the unidirectional transmission can clearly be grasped [7].

The example two-layer nanostructure is schematically shown in Fig. 1(a). The details are shown in Ref. [7]. As shown in the inset of Fig. 1(b), the difference between polarization conversion efficiency from $X$ to $Y$ in the forward direction and that from $Y$ to $X$ in the backward direction emerges, referred to as “unidirectionality”, especially in the wavelength region between 900 nm and 1200 nm. Furthermore, as shown in Fig. 1(b), such unidirectionality is maximized when the two layers are separated by an appropriate distance whereas either too short or too large gap distances destroy the unidirectionality. Meanwhile, the forward- and backward-direction polarization conversion efficiency is theoretically estimated as the transfer of momentum based on the angular spectrum representation of optical near-fields. Figure 1(c) shows the theoretically estimated unidirectionality as a function of inter-layer distance, which agrees well with the numerical simulations shown in Fig. 1(b). Also, the relation between the structural symmetry/asymmetry in the assumed nanostructures and the resultant unidirectionality agree well between theory and simulations.

Figure 1 Direction-dependent polarization conversion: angular-spectrum-based theory and simulations

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REFERENCES