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Review

Controlling light with plasmonic multilayers

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Abstract

Recent years have seen a new wave of interest in layered media – namely, plasmonic multilayers – in several emerging applications ranging from transparent metals to hyperbolic metamaterials. In this paper, we review the optical properties of such subwavelength metal–dielectric multilayered metamaterials and describe their use for light manipulation at the nanoscale. While demonstrating the recently emphasized hallmark effect of hyperbolic dispersion, we put special emphasis to the comparison between multilayered hyperbolic metamaterials and more broadly defined plasmonic-multilayer metamaterials A number of fundamental electromagnetic effects unique to the latter are identified and demonstrated. Examples include the evolution of isofrequency contour shape from elliptical to hyperbolic, all-angle negative refraction, and nonlocality-induced optical birefringence. Analysis of the underlying physical causes, which are spatial dispersion and optical nonlocality, is also reviewed. These recent results are extremely promising for a number of applications ranging from nanolithography to optical cloaking.

Keywords: Nanophotonics; Metamaterials; Plasmonics; Multilayered structures

Contents

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1. Introduction

Propagation of electromagnetic waves in layered media has been studied for a long time [1–4]. In recent years, such media are found to attract growing scientific interest due to their unique electromagnetic properties which have been discovered recently. Particularly, it was realized that optical metamaterials formed by multilayered metal–dielectric nanostructures shown in Fig. 1(a) have a range of striking optical properties and various applications spanning from the realization of indefinite media [5], subwavelength imaging [6,7], negative refraction [8] and cloaking [9] to mimicking black holes [10].

In the past, only structures consisting of dielectric layers were studied as it was commonly assumed that metals are opaque in the optical domain. Indeed, if the metal slab L is thicker than the skin depth δ (around 10–15 nm for optical frequencies), almost no transmission through the metal occurs, similarly to the case of total internal reflection from a dielectric slab for the incident angle (θ) exceeding the critical angle (θ_c), as shown schematically in Fig. 1(b). However, when metal is mixed with dielectric at the wavelength scale to form a multilayer structure [Fig. 1(b), third case], it was astonishingly found to result in new kind of optical behavior: even though there are many metal layers with total thickness much larger than δ, light was found to pass through the structure [11]. This effect (*photonic transparent metal*) occurs because the multilayered metal–dielectric structure supports propagating waves formed by evanescent waves in each layer. The incident plane wave excites evanescent waves that is transferred by the structure via plasmon-mediated tunnelling mechanism [12–15] often referred to as *resonant plasmon tunnelling* [16].

Further reducing the thicknesses of metal and dielectric layers in the multilayer from about a quarter of a wavelength [19] to about $\lambda_0/10$ (where $\lambda_0 = \omega/c$ is the free-space wavelength of light) brings the structure to what would be ordinarily regarded as deeply subwavelength or metamaterial regime. Facilitated with recent success with fabricating good-quality metal layers with thicknesses smaller than δ, such *multilayer plasmonic metamaterials* are following the present-day trend of bringing optics to the nanoscale.

It is remarkable that these multilayer metamaterials can go beyond showing increased transmittance

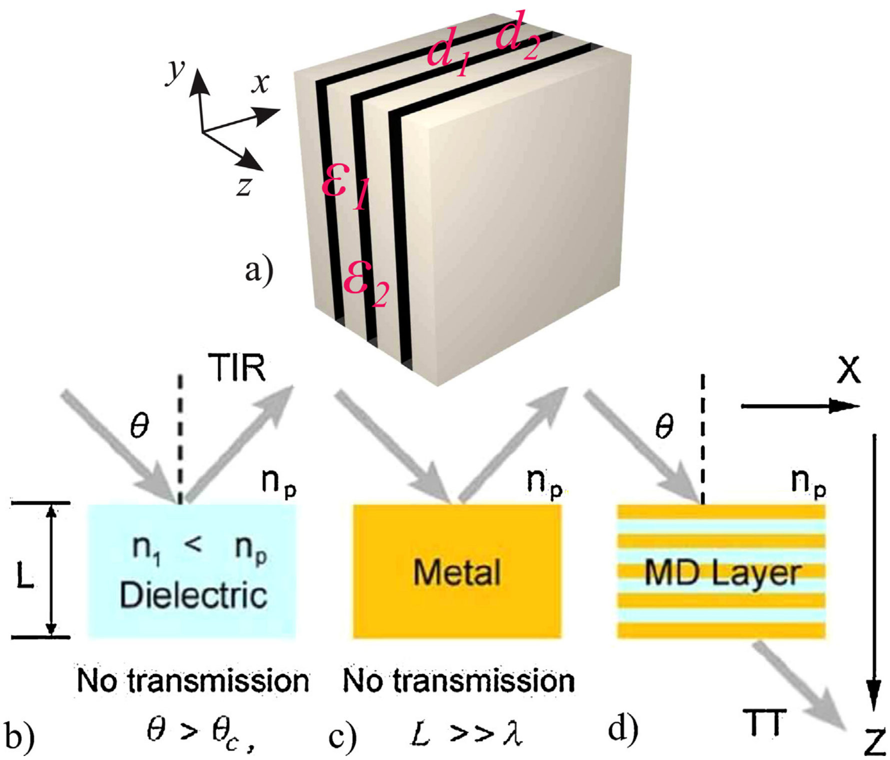

Fig. 1. Plasmonic multilayer and transition from total internal reflection to total transmission. (a) A dielectric slab has refractive index $n < n_p$ and total internal reflection occurs for incident angles above the critical one, (b) a metal slab with total reflection at any angles, and (c) an alternating metal and dielectric multilayer that demonstrates total transmission. Reproduced with permission from Ref. [24].