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Antireflection layers in low-scattering plasmonic optics ☆

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Abstract

Antireflection layers for plasmonic optical elements analogous to conventional antireflection coatings are proposed and numerically investigated. It is shown that the average surface plasmon reflectance can be decreased by several orders of magnitude simultaneously with the suppression of the parasitic scattering of the surface plasmon energy. The application of the proposed approach to a binary plasmonic microlens array is considered as an example. The presented approach can be used for the design of other plasmonic elements working in transmission.

Keywords: Surface plasmon polariton; Antireflection coating; Parasitic scattering suppression; Electromagnetic optics; Rigorous coupled-wave analysis; Microlens array

1. Introduction

Surface electromagnetic waves propagating in various dielectric and metal–dielectric structures have attracted considerable research interest during the recent years due to both their fundamental properties and potential applications [1]. Most studied are surface plasmon polaritons (SPP) propagating along the interfaces between metal and dielectric media. Another considered type of surface waves are the so-called Bloch surface waves (BSW) propagating at the interfaces between a photonic crystal and a homogeneous medium.

Several types of 2D optical elements for steering the surface wave propagation (e.g. for surface wave reflection and focusing) have been proposed, in particular, dielectric structures located directly on the surface of the metal or the photonic crystal [2–9]. Among others, prisms and lenses [2], Bragg gratings [3] and gradient-index optical elements [5] were proposed and experimentally demonstrated for SPP. Recently, 2D dielectric lenses for focusing BSW were also created [8,9]. The operating principle of most of these structures is based on the phase modulation of the incident surface wave. Along with the absorption losses intrinsic in plasmonic structures, parasitic scattering losses at the interfaces between different dielectric media are one of the major mechanisms decreasing the efficiency of such elements [10,11]. These losses are caused by the transverse field profile mismatch of the surface wave (SPP or BSW) across the interface and can reach up to 30% of energy at a single interface. Similarly to the conventional optical elements,

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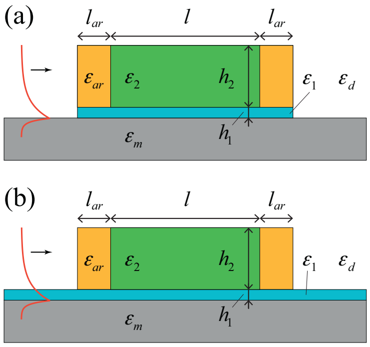

Fig. 1. Considered structure geometries: a two-layer dielectric block without ((a), geometry A) or with ((b), geometry B) a continuous dielectric layer.

the efficiency of the 2D optical elements working in transmission can be also sufficiently decreased because of the partial reflection of the incident wave.

In our previous works, we have proposed an approach for the design of low-scattering plasmonic optics based on the utilization of two-layer structures (dielectric–dielectric–metal plasmonic waveguides) made of isotropic materials [12–14]. The proposed approach is much simpler than other previously developed techniques based on the usage of anisotropic metamaterials [11,15]. It was shown that the approach presented in [12–14] allows decreasing the average parasitic scattering losses by an order of magnitude by means of partial matching of the transverse field profiles of the incident SPP and the plasmonic mode inside the element.

In the present work, we propose and study numerically the antireflection layers (analogue of conventional antireflection coatings) for plasmonic optical elements with parasitic scattering suppression. As an application example, design of a binary plasmonic microlens array is considered.

2. SPP antireflection layers

Let us first consider as a model problem the SPP propagation through a two-layer dielectric block with the length l, to which the antireflection layers can be added. Two structure geometries are studied (Fig. 1), the differences between them being the material of the antireflection layers (blocks) and the presence or absence of a continuous dielectric layer on the metal surface outside the block. SPP (Fig. 1(a), geometry A) or the mode of the dielectric–dielectric–metal plasmonic waveguide (Fig. 1(b), geometry B) is normally incident at a two-dimensional structure (structure properties do not change in the direction perpendicular to the figure plane). Let us note that the continuous dielectric layer in geometry B serves as a protective layer preventing the degradation of the metal surface. Fig. 1 shows the dielectric blocks with two attached antireflection layers on the left and right sides having equal length l_{ar}. Dielectric blocks without antireflection layers and with the left antireflection layer only were also simulated.

For both geometries, the following parameters similar to the parameters of the examples considered in our previous works [13,14] were used in the simulations: free-space wavelength $\lambda_0 = 800$ nm, $\varepsilon_m = -24.06 + 1.51i$ (corresponds to Au) [16], $\varepsilon_d = 1$, $\varepsilon_1 = 1.45^2$, $\varepsilon_2 = 1.7^2$, and $h_2 = 1$ μm. The thickness of the first layer h_1 was equal to 62 nm and 38 nm for geometries A and B, respectively. In both cases, the h_1 value was chosen to minimize average parasitic scattering losses in the case of SPP transmission through a dielectric block without antireflection layers. Block length was varied from 0 to 1 μm.

For geometry A, $\varepsilon_{ar} = \varepsilon_1 = 1.45^2$, and for geometry B, $\varepsilon_{ar} = 1.3^2$ (the latter was chosen to provide a nearly optimal value of the effective refractive index of the plasmonic mode in the antireflection layer as described below). Antireflection layer lengths l_{ar} were calculated from the following expression:

$$l_{ar} = \frac{\lambda}{4n'_{eff,ar}}, \quad (1)$$

where $n'_{eff,ar} = Re\{n_{eff,ar}\}$ is the real part of the effective refractive index (propagation constant normalized by the wave number) of the plasmonic mode in the antireflection layer. Eq. (1) is identical to the expression defining the thickness of conventional antireflection coatings. For geometry A $n_{eff,ar} = 1.5175 + 0.0046i$, and for geometry B $n_{eff,ar} = 1.3811 + 0.0044i$. In the latter case, the $n'_{eff,ar}$ value is close to the optimal value $n'_{eff,ar,opt} = 1.3642$ which can be found from the expression:

$$n'_{eff,ar,opt} = \sqrt{n'_{eff,inc} n'_{eff,block}}, \quad (2)$$

where $n'_{eff,inc}$ and $n'_{eff,block}$ are the real parts of the effective refractive indices of the incident SPP (or plasmonic mode) and the plasmonic mode propagating inside the block, respectively. Eq. (2) is also identical to the equation defining the optimal refractive index of a conventional antireflection coating providing minimal reflection possible. The values of l_{ar} found from Eq. (1) are equal to 132 nm and 145 nm for geometries A and B, respectively.

Let us note that since the studied reflection and scattering suppression effects are not resonant, the used parameters are not specific and reflection and scattering suppression similar to the results presented below can be