Low-scattering Bragg gratings for surface plasmon polaritons

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Abstract. In this work, diffraction efficiency and scattering and absorption losses in dielectric Bragg gratings for surface plasmon polaritons (SPP) are numerically studied using the Fourier modal method. It is shown that the main reason behind the low efficiency of such Bragg reflectors is the out-of-plane parasitic scattering of SPP at the grating ridges. As an efficient technique for decreasing the scattering losses, an increase in the grating period at a fixed aspect ratio is proposed, which leads to a 30% increase in the reflector efficiency. We also show that the utilization of two-layer grating ridges makes it possible to increase the reflectivity by another 3.5%.

1. Introduction

One of the promising research directions in nanophotonics is plasmonics, which, in particular, studies surface plasmon polaritons (SPP) — surface electromagnetic waves supported by metal-dielectric interfaces. For steering SPP propagation, various plasmonic elements such as dielectric prisms [1], lenses [2], waveguides [3] and Bragg reflectors [4] have been proposed. The main drawback of the most of these elements consists in the absorption losses in metals and in the parasitic out-of-plane scattering losses at the element boundaries. In a previous work of some of the present authors, a simple approach to the suppression of the SPP parasitic scattering was proposed [5], based on the utilization of two-layer ridges constituting the dielectric plasmonic element. This configuration provides partial matching of the transverse field profile of the plasmonic modes outside the element and in it. It was demonstrated that the two-layer structure enables decreasing the scattering losses by an order-of-magnitude. In the present work, this approach is applied to Bragg reflectors for SPP designed for the case of normal incidence.

2. Bragg gratings for surface plasmon polaritons

Figure 1(a) shows the geometry of a Bragg grating for SPP. The grating consists of several dielectric ridges with height $h_{gr}$ and width $l_1$ located on the surface of a metal layer with thickness $h_m$ and dielectric permittivity $\varepsilon_m$. The ridges are periodically arranged with the period $d$ ($l_2 = d - l_1$ is the distance between the adjacent grating ridges). The dielectric permittivity of the superstrate is $\varepsilon_d$.

The values of $l_1$ and $l_2$ in the case of normal incidence of SPP are related by the expression
where $k_1, k_2$ are the propagation constants of the plasmonic modes in the ridges and between them, respectively. The propagation constant of the incident SPP (and the SPP propagating between the ridges) equals

$$k_2 = k_0 \frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d},$$

where $k_0 = 2\pi/\lambda_0$, and $\lambda_0$ is the free-space wavelength. The propagation constant of the plasmonic mode $k_i$ at a finite thickness of the dielectric ridge can be found using the dispersion relation for the TM-polarized modes of the slab waveguide [7,8]:

$$\tanh\left(\frac{\gamma_j h_{gr}}{d}\right) = -\frac{\gamma_j \varepsilon_{gr} (\varepsilon_d \gamma_m + \varepsilon_m \gamma_d)}{\varepsilon_d \varepsilon_m \gamma_{gr}^2 + \varepsilon_d \varepsilon_m \gamma_d \gamma_m},$$

where $\gamma_j = k_j^2 - k_0^2 \varepsilon_j, j = m, d, gr$.

**Figure 1.** Geometry of the structure: (a) Bragg reflector for SPP, (b) two-layer configuration of the grating ridge.

One of the solutions of Eq. (1) with respect to $l_1$ and $l_2$ can be represented as

$$l_i = \frac{\lambda_0 (2n+1)}{4 \text{Re}(k_i/k_0)}, i = 1, 2, n = 0, 1, 2, ...$$

We will call the gratings with the $l_i$ and $l_2$ values obtained from Eq. (4) at $n = 0$ and at $n = 1$ a zero-order and a first-order Bragg gratings, respectively. It is important to note that the efficiency of zero-order gratings with reasonable aspect ratios ($h/l_i \leq 3$) is relatively low, since the parasitic scattering losses in this case reach 40–50%. The utilization of a first-order grating enables increasing the ridge height while maintaining the aspect ratio, which, as shown below, makes it possible to significantly reduce the scattering losses. Another approach to the suppression of the parasitic scattering is the utilization of the two-layer geometry of the grating ridge described above (Fig. 1(b)).

Let us replace the ridge with dielectric permittivity $\varepsilon_{gr}$ and the height $h_{gr}$ by a ridge consisting of two materials with the dielectric permittivities $\varepsilon_1$ and $\varepsilon_2$ ($\varepsilon_1 < \varepsilon_2$), and the heights $h_1$ and $h_2$, respectively. Assuming that the thickness of the upper layer $h_1$ is large enough, we can find the propagation constant of the plasmonic mode in such a ridge by the same dispersion relation (3) by replacing $\varepsilon_{gr}$ with $\varepsilon_1$, and $\varepsilon_d$ with $\varepsilon_2$ and using $h_1$ as the thickness value. At fixed dielectric permittivities, the $h_1$ value providing partial field profile matching (and, consequently, a decrease in parasitic scattering) can be found analytically from Eq. (3) and the condition $\text{Re}(\gamma_2) = \text{Re}(\kappa_d)$, where $\kappa_d = \sqrt{k_d^2 - k_0^2 \varepsilon_d}$.

**3. Numerical simulation results and discussion**

The simulation of the SPP diffraction on the investigated Bragg gratings was carried out using an efficient in-house implementation of the Fourier modal method [9] extended for the solution of the integrated optics problems [10].
Let us first consider a single-layer SPP Bragg reflector similar to the example considered in [6] and having the following parameters: design free-space wavelength $\lambda_0 = 1100$ nm, $\varepsilon_m = -52.39 + 4.02i$ (Au), $h_m = 300$ nm (at this thickness, the metal film can be considered infinitely thick in the simulations), $\varepsilon_{gr} = 1.49^2$ (SiO$_2$). If the aspect ratio is fixed and equals 3, the zero-order and first-order Bragg reflectors have the following parameters: $l_1 = 183.5$ nm, $l_2 = 272.4$ nm, and $h_{gr} = 550$ nm, and $l_1 = 542$ nm, $l_2 = 817.1$ nm, and $h_{gr} = 1626$ nm, respectively. For the sake of comparison, let us also consider a zero-order Bragg reflector with a greater aspect ratio of 8 with the parameters $h_{gr} = 1446$ nm and $l_1 = 180.7$ nm. The reflectance and transmittance spectra of these reflectors consisting of $N = 15$ periods are shown in Fig. 2(a). As “reference” spectra, reflectance and transmittance of a Bragg mirror calculated for plane waves and consisting of the same number of periods are shown. The thicknesses of the layers of this conventional Bragg mirror are also found from Eq. (4), thus, the refractive indices of the layers coincide with the effective indices of plasmonic modes in the Bragg reflector for SPP. Fig. 2(a) shows that an increase in the grating ridge height enables reducing the scattering losses and increasing the efficiency, however, it simultaneously leads to an increase in the aspect ratio, which can make the structure experimentally unfeasible.

![Figure 2](image-url)

**Figure 2.** Reflectance (blue curves) and transmittance (black curves) for zero-order (a) and first order (b) Bragg gratings: single-layer SPP gratings with aspect ratio 3 (solid curves), plane-wave gratings (dash-dot curves), and single-layer SPP grating with aspect ratio 8 (a) or two-layer SPP grating (b) (dashed curves); vertical red lines show the boundaries of the band gap calculated for the plane-wave structure.

As the next example, let us investigate the efficiency of a first-order two-layer Bragg reflector with the following parameters: $\varepsilon_i = 1.3^2$, $\varepsilon_r = 1.49^2$, $l_1 = 550.7$ nm, $h_1 = 40$ nm, $h_2 = 1586$ nm (the total ridge height $h_{gr} = h_1 + h_2 = 1626$ nm, which coincides with the ridge height of the zero-order Bragg reflector with a larger aspect ratio described above). Figure 2(b) shows reflectance and transmittance spectra for first-order Bragg mirrors with and without scattering suppression at $N = 15$.  

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It follows from Figs. 2(a) and 2(b) that the efficiency of a zero-order Bragg grating with the aspect ratio limited by 3 is indeed low ($R = 48\%$, $L = 47.4\%$ at the 1100 nm wavelength) as compared to the “unrealistic” grating with the aspect ratio equal to 8 ($R = 82.5\%$, $L = 17.1\%$). The utilization of the first-order grating enables increasing the reflectance by 30% ($R = 78\%$, $L = 21.9\%$) as compared to the zero-order grating with the same aspect ratio of 3. The introduction of the two-layer geometry allows one to increase reflectance by a further 3.5%. However, it is important to note that the spectral width of the band gap decreases approximately threefold if the grating order is increased from 0 to 1.

Figure 3 shows the reflectance and transmittance vs. the length of the Bragg reflectors. It follows from Fig. 3 that the sufficient number of periods, after which the reflectance does not significantly increase is the same for the zero-order and first-order gratings and equals $N = 8$. Of course, at the same number of periods the dimensions of the first-order grating are three times larger than those of the zero-order grating.

Figure 3. Reflectance (blue curves) and transmittance vs. total structure length for SPP Bragg gratings: first-order two-layer grating (dashed curves) and zero-order single-layer grating (solid curves). Markers denote actual data points corresponding to different numbers of periods; curves are guides to the eye.

4. Conclusion
In conclusion, let us summarize the presented results. It is shown that the utilization of a first-order (long-period) Bragg reflector for surface plasmon polaritons instead of a zero-order reflector enables increasing the efficiency (reflectance) by 30% by reducing the parasitic scattering losses. The introduction of a two-layer ridge geometry allows one to increase the efficiency by another 3.5%. The obtained results may find use in the design of the “2D” plasmonic optical elements for various applications including optical filtering [4], sensing [11] and analog optical computing [12, 13].

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