Resonant TM transmission through metallized variable depth grating

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Abstract. Symmetrical dielectric/metal/dielectric structure based on variable depth grating was fabricated and characterized. Plasmon-mediated resonant TM transmission across optically thick aluminium layer is measured for a continuous and large set of undulation depth, the existence of optimized depth is experimentally demonstrated alongside other plasmonic and interference features. The correspondence with rigorous GSMCC numerical simulations is confirmed.

1. Introduction
Surface plasmon resonance (SPR) is a well-known and extensively studied phenomenon in nanooptics research [1-2]. Due to its unique properties of strong field enhancement, high bulk and surface sensitiveness and subwavelength energy confinement SPR is utilized nowadays in diverse applications like biochemical sensing, optical interconnects, Raman spectroscopy and plasmonic nanolithography [3-5].

Resonant TM transmission is an enhanced plasmon-mediated light transmission through optically thick metallic films with and without holes. This effect has a number of advantages over the conventional SPR, for example improved signal-to-noise ratio and simple collinear experimental setup, what is in demand for high-sensitive sensor applications [6]. A common way to excite plasmonic modes and provide energy transfer is the surface nanostructuration, for example sinusoidal corrugation (with predefined period) of metallic layer in 1D case (Fig.1a). Geometrical parameters of corrugation (i.e. grating depth) significantly influence the quality of plasmonic coupling at specified wavelength and can be optimized numerically. In practice, however, fabricated structure can demonstrate the transmission sufficiently different from the expected one because of certain reasons [7], thus an experimental optimization procedure is needed. In this work we propose such a technique for the search of optimal grating depth. We fabricated dielectric/metal/dielectric layered structure based on variable depth grating (0–100 nm) and measured the wavelength-depth resolved transmission map. The existence of optimal grating depth for ≈45% resonant transmission is experimentally demonstrated and numerical verification using rigorous Generalized Source Method in Curvilinear Coordinates (GSMCC) [8] is presented.
2. Sample fabrication

Laser Interference Lithography (LIL) is a well-established large area maskless surface patterning technique for realizing periodic structuration at the micro- and nano-scale [9]. The typical fabrication process for a 1D diffractive grating requires a one-shot exposition of the photoresist layer in the interference field of two coherent beams. This approach, however, leads to equal grating depth at any surface point, as the interference pattern is strictly periodical (with period \( \Lambda_1 \)). In order to fabricate a variable depth grating we introduce a second exposition with the same laser intensity and illumination time, but slightly perturbed fringe period \( \Lambda_2 \). The sum of functions with close periods \( \Lambda_1 \approx \Lambda_2 \) leads to the well-known Moiré effect:

\[
\sin \left( \frac{2\pi}{\Lambda_1} x \right) + \sin \left( \frac{2\pi}{\Lambda_2} x \right) \approx 2 \sin \left( \frac{2\pi}{\Lambda_1} x \right) \cos \left( \frac{2\pi}{2\Lambda_1^2 / \Delta \Lambda} x \right) 
\]

(1.1)

As \( \Lambda_1 \approx \Lambda_2 \), Eq. (1.1) represents the sinusoidal intensity pattern of nanoscale period \( \approx \Lambda_1 \) modulated by sinusoid of large macroscopic period \( \Lambda_{\text{macro}} \approx 2\Lambda_1^2 / \Delta \Lambda \). In this work \( \Lambda_1 = 301 \text{ nm} \), \( \Lambda_{\text{macro}} = 8.8 \text{ cm} \), and \( \Lambda_{\text{macro}} / \Lambda_1 \approx 3 \cdot 10^5 \) is used. The fabrication process is sketched in Fig. 2a:

![Fabrication Process](image)

Fig. 2. a) Three steps of sample fabrication (from left to right): 1-creating of variable depth grating using beats envelope (Moiré effect) in S1805 photoresist; 2-metallization of grating surface with aluminum, metal thickness 17 nm; 3-the final deposition of photoresist on the top of metallized grating. b) SEM image of metallized grating surface (Fig.2b) demonstrates the absence of metal islandization, what is important for effective excitation of non-localized plasmons.

The glass surface (BK7) was cleaned using three-step wet bench procedure (acetone, ethanol and water baths), after that a thin (~300 nm) layer of the photoresist S1805 was deposited by spin-coater. This photosensitive layer was then exposed twice with a slightly different periods and developed under optimized duration to get the surface nanostructuration with desired depth variation (step 1 at Fig.2a). Optically thick Al film (17 nm) was then deposited by an evaporation process on the structured surface and covered again by the same resist in order to obtain a symmetrical dielectric/metal/dielectric geometry (steps 2-3 at Fig.2a accordingly). The thicknesses of lower and upper dielectric claddings are \( \approx 250 \text{ nm} \) and \( \approx 700 \text{ nm} \), respectively. The SEM image of metallized grating surface (Fig.2b) demonstrates the absence of metal islandization, what is important for effective excitation of non-localized plasmons.
3. Sample characterization

We used an AFM to measure the metallized grating profile (Fig.2a, second step) and obtained the dependence of grating depth on surface position (envelope function in Eq. (1.1)), see Fig.2c. The sample continuously covers all possible depths in range from 0 to 105 nm and allows to measure transmission spectra for this range simply by shifting the sample and illuminating different parts of the surface.

The 2D map of resonant transmission at normal incidence across our sample (Fig.2a, third step) as a function of wavelength and grating depth is presented in Fig. 3:

![Image](image_url)

Fig.3. Measured transmission map in visible range for continuously changing set of depths (red coordinate axis on the right), corresponding to different positions on the same fabricated sample (black coordinate axis on the left). The existence of optimal depth for the maximum resonant transmission (point A) is demonstrated.

It consists of series of particular spectra corresponding to transmission through different grating areas and demonstrates a number of features. First of all, it has an axial symmetry (horizontal black dashed line in Fig.3) which originates from axial symmetry of sinusoidal grating envelope with respect to coordinate ≈1.1 cm (see Fig.2c). Vertical lines of relatively high transparency (denoted as L1-L3 in Fig.3) correspond to transmission variations analogous to those in Fabry–Pérot interferometer (with the interference area in our sample mainly in the upper dielectric cladding) and their resonant wavelengths can shift with changing of dielectric claddings thickness. Consequently, the presence of these lines in measured transmission spectrum and their strict vertical orientation together with pronounced axial symmetry of Fig.3 demonstrates the fabrication quality. The most important feature of Fig.3 is the existence of an optimal grating depth (≈50 nm) with the highest experimentally achievable transmission (≈45% in our geometry), denoted as white point A. The total area of plasmon-mediated resonant transmission is quite large in the sense of depth, excluding point A it contains also two branches (shoulders) of long- and short-range plasmonic modes (white dashed lines 1 and 2 in Fig.3 respectively) in the finite-thickness metallic layer.

To clarify the resonant transmission spectrum deformations with varying grating depth we plotted the one-dimensional experimental spectra for several depths (see Fig.4a). Two shoulders of plasmonic resonances are clearly visible. Fig.4b shows the experimental dependence of resonant transmission on grating depth, which is to be compared with theoretical model curve in Fig.1b. At last, Fig.4c demonstrates a good correspondence between the theory (GSMCC) [8] and the experiment on an example of transmission through optimized grating depth 52 nm.
Fig. 4. a) Experimental transmission spectra in the vicinity of plasmonic excitations for several grating depths denoted by numbers with the same colors as a corresponding spectrum. Lines L2 and L3 are also visible; b) Maximum (resonant) transmission as a function of depth (to be compared with an example in Fig.1b); c) Comparing of measured data (blue dots) with simulation based on rigorous GSMCC numerical method (red line).

4. Conclusion

In conclusion, variable depth gratings offer new possibilities in fields of plasmonics and optical security elements [10]. In this work we demonstrated that such a grating is a promising instrument for experimental optimizing needs, using an example of optimized resonant transmission across an optically thick metallic layer. We believe that such approach can improve the behavior and widen the applicability of existing optical devices based on nanogratings like (bio)chemical sensors.

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