Observation of Hybrid States of Tamm and Surface Plasmon-Polaritons in Photonic Crystals

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Abstract: Experimental observation of Tamm plasmon-polariton and surface plasmon-polariton hybrid mode is reported. Such mode is excited in one-dimensional photonic crystal terminated by semitransparent metal film under conditions of total internal reflection for TM-polarized light.
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1. Introduction

Tamm plasmon-polaritons (TPP) in photonic crystals (PC) are optical analogues of electronic density localization at the boundary of periodic atomic potential [1] and appear as electromagnetic field localization at the boundary of photonic crystal and metal [2]. Unlike surface electromagnetic waves and surface plasmon-polaritons (SPP) Tamm plasmon-polaritons do not have phase-matching conditions for in-plane wave vector, thus TPP can be excited for any angle of incidence [3]. However boundary conditions for out-of-plane wave vector are critical for TPP. Experimentally these states manifest themselves as narrow absorption resonances in reflectance spectra of Me/PC systems [4].

The TPP coupled with other excitations such as excitons or microcavity modes have been intensively studied last years [5,6] due to prospectives of the TPP application in new compact lasers and sensors [7]. Such states are called "hybrid" ones and can be detected as a series of several non-overlapping resonances in reflectance spectra.

In a photonic crystal terminated by semitransparent metal film SPP can emerge at the metal surface under total internal reflection, while conditions of TPP at the metal/PC interface excitation would be satisfied automatically because TPP can be excited for any angle of light incidence. Therefore one can expect appearance of SPP-TPP hybrid state.

2. Samples and setup

The studied samples consisted of 6 pairs of ZrO_2/SiO_2 quarter-wavelength-thick layers deposited on quartz substrate using thermal evaporation. The layer thicknesses obtained from the scanning electron microscopy image of the sample cleavage are 110 nm (ZrO_2) and 145 nm (SiO_2), that corresponds to the Bragg wavelength of $\lambda_B = 850$ nm. According to the calculations optimal thickness of the top most layer was estimated as 225 nm, therefore additional 80 nm layer of SiO_2 was deposited on the PC sample. The resultant structure was covered by a 30-nm-thick gold film allowing both good field localization in the TPP mode and possibility of the SPP excitation.

Reflection spectra were measured with the 1-nm resolution using polarized collimated beams. For measurement of angular dependences the θ-2θ goniometer was used providing 0.005° accuracy.

3. Experimental results

Figure 1 shows image plots of reflection coefficient spectra as a function of the angle of incidence for the TM polarization of incoming light, measured (Fig.1a) and calculated (Fig.1b). TPP dip inside photonic band-gap is observed for incident angles less than the angle of total internal reflection (about 41° for used prism). Both PBG and TPP resonances are blue-shifted with the incident angle increase as perpendicular component of the wave vector decreases. TPP resonance appears again at $\theta = 43°$ and $\lambda = 620$ nm. For the angles exceeding the angle of total internal reflection phase matching conditions for SPP excitation are satisfied. The SPP dip starts from $\theta = 42°$ and $\lambda = 1000$ nm and rapidly blue-shifts with increasing the angle of incidence. However, dispersion curve of SPP in Au/PC sample is considerably red-shifted comparing to the dispersion curve of SPP in gold film. Inset in Figure 1b shows reflection coefficient spectrum as a function of angle of incidence for a reference sample — 30-nm-thick gold film. Dip corresponding to SPP excitation appears at 42°. Spectral position of SPP in the reference sample at 50° is approximately 520 nm while spectral position of SPP in the Au/PC sample at 50° is about 610 nm due to the coupling with TPP which leads to repulsion of TPP and SPP resonances.

For TE polarization of incoming light SPP propagation is forbidden. Thus TPP is excited solely. Spectral position of the TPP resonance shifts to shorter wavelengths approaching PBG edge. This is in an agreement with numerical calculations.

Numerical calculations were also performed to study how coupling of TPP and SPP depends on the thickness of the gold layer. Image plots of reflection coefficient spectra as a function of the angle of incidence for the TM polarization of incoming light for different thicknesses of the Au layer are shown in Fig. 2. Parameters of the model PC structure were the same as in experiment. With increasing thickness of gold layer splitting of TPP and SPP components of hybrid state decreases since normalized overlap integral of exponential tails of SPP and TPP in metal diminishes. For the films thicker than 60 nm TPP and SPP do not sense each other and repulsion of their dispersion curves becomes negligible.

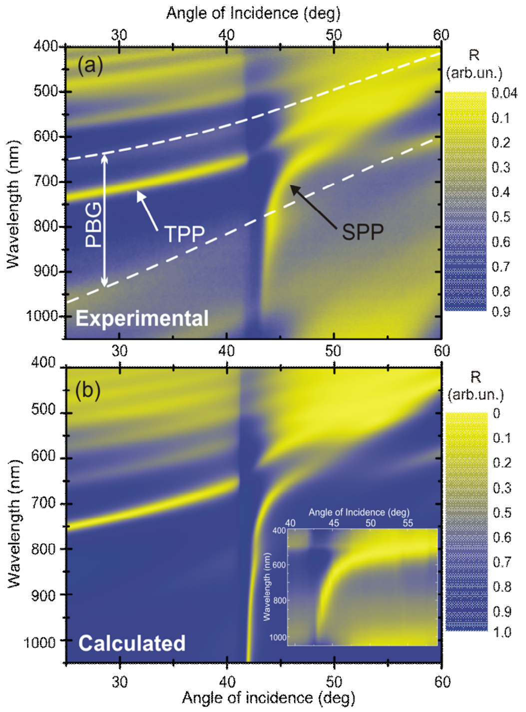

Fig.1 (Color online) (a) Image plot of experimental reflectivity (R) spectrum of Au/PC sample for TM polarization. Arrows indicate dispersion curves of Tamm plasmon-polariton and surface plasmon-polariton. Dashed curves indicate photonic band-gap. (b) Image plot of calculated reflectivity spectrum for TM polarization. Inset shows image plot of experimental reflectivity spectrum of a reference gold film for TM polarization. Yellow stripe corresponds to the SPP dispersion curve.

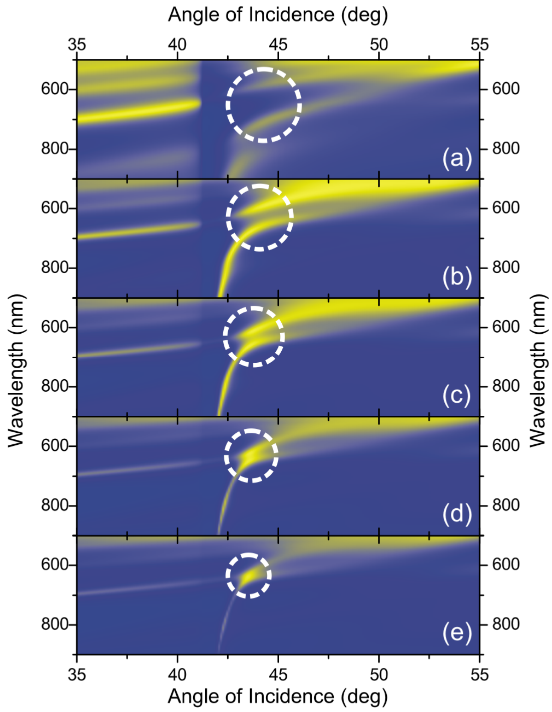

Fig. 2 (Color online) Image plots of reflectivity spectra for TM polarization calculated for thicknesses of gold layer of 20 nm (a), 40 nm (b), 50 nm (c), 60 nm (d), 70 nm (e). Dashed circles emphasize spectral-angular region of TPP and SPP dispersion curves repulsion.

4. Conclusions

In conclusion, we have obtained experimental evidence of excitation of Tamm and surface plasmon-polaritons hybrid mode in Au/1D PC structure. For TM polarized incoming light these two surface modes exist on the opposite surfaces of metal film. Tamm and plasmon components of hybrid mode are revealed as two non-overlapping resonances. Their coupling leads to repulsion of dispersion curves (75 nm for 30-nm-thick gold film), which can be used for creating tunable plasmonic filters or sensors.

5. References

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