Femtosecond dynamics of Tamm plasmon-polaritons relaxation

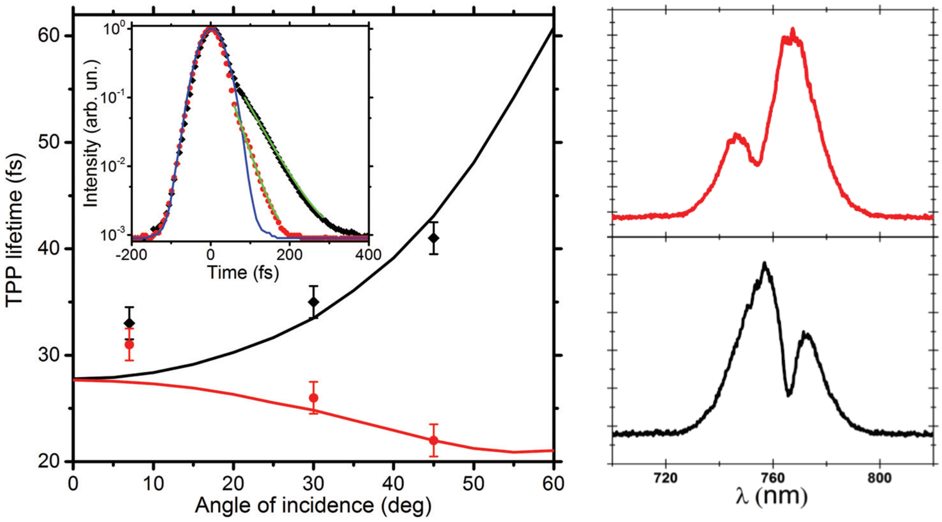
V.O. Bessonov, B.I. Afinogenov, A.A. Popkova, A.A. Fedyanin
Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
bessonov@nanolab.phys.msu.ru

Abstract: The lifetime of the Tamm plasmon-polaritons excited in a 1D photonic-crystal/metal-film structure is experimentally found to vary from 20 fs to 40 fs depending on polarization and incident angle of light.

Tamm plasmon-polariton (TPP) is an optical analogue of Tamm state and appears as spatial localization of the electromagnetic field near the boundary of one-dimensional photonic crystal (PC) (distributed Bragg reflector) and a metal film. TPP can be detected experimentally as a narrow resonance in the reflectance or transmittance spectrum of a PC/metal structure. The spectral position of TPP resonance corresponds to photonic band gap spectral range and governed by thickness of the PC topmost layer adjacent to the metal [1]. Contrary to surface plasmon-polariton TPP occurs at any angles of incident light for both TE and TM polarizations, and it excitation does not require sophisticated optical schemes (such as Kretchmann scheme). The peculiarities of TPP optical properties led to considerable interest to the design, fabrication and study of TPP-supported structures in the past several years. The TPP and hybrid TPP modes [2] have been proposed for use in novel optical devices such as lasers [3], sensors [4] and nonlinear optical elements [5]. The interest in study of ultrafast optical properties of TPP is caused by it's potential using in compact ultrafast photonic switchers and modulators. The dynamics of TPP excitation was discussed in [6] but the TPP was excited in the complicated structure and the only indirect measurements of TPP lifetime were demonstrated. In present work, the ultrafast relaxation dynamics of TPP exited in the PC/metal structures is measured using intensity cross-correlation scheme. The TPP lifetime is obtained for different polarizations and incident angles of light, and compared with one obtained from numerical calculations.

The studied samples were designed to support the excitation of TPP in spectral range of the tuning Ti:sapphire laser. The PC/metal samples consisted of 7 pairs of SiO_2 and Ta_2O_5 quarter-wavelength-thick layers (with thicknesses of 130 nm and 92 nm) covered with 30-nm-thick silver film. To avoid the silver film degradation, the structure was covered with 20-nm-thick of Al_2O_3 layer which did not affect the optical properties of the TPP. The layers films were deposited using the thermal evaporation technique, and the quality of the deposition was controlled using a scanning electron microscope. The bare PC of the same parameters and a 30-nm-thick silver film on substrate were used as reference samples. Intensity cross-correlation scheme was based on Coherent Micra Ti:sapphire laser with pulse compressor which provided the 1-nJ pulses with a duration of 50 fs (bandwidth of 25 nm) in the sample area. The signal beam reflected from the sample was superposed with the reference beam in a BBO crystal using focusing parabolic mirror. The dependence of the intensity of non-collinear second harmonic radiation generated in the BBO crystal on delay between signal and reference pulses was measured with 1 fs resolution using a lock-in amplifier. In all experiments the excitation of TPP by signal beam was performed from the side of the metal layer and controlled by spectroscopy of laser pulses reflected from the sample.

First, cross-correlation functions (CFs) of pulse reflected from the reference samples were measured. The CFs shape was in an excellent agreement with Gaussian fit. The CFs of p- and s-polarized pulses reflected from the PC/metal sample at 45° are shown in the inset of Fig. 1a with red circles and black squares, respectively. The corresponding spectra of reflected pulses shown in Fig.1b demonstrate the dips related to the TPP excitation. One can see tails on the trailing edges of the CFs. These tails are the result of a delayed reflection of light, which was trapped into the TPP mode. Tails can be well described by function $y \sim \exp(-t/\tau)$ (shown with green lines), where τ is the TPP lifetime. The lifetime of TPP was found to be 20 fs for p-polarized light and 40 fs for s-polarized light at a 45° angle of incidence. The CFs of p- and s-polarized laser pulses were measured at different angles of incidence. Fig. 1a shows the TPP lifetimes that were obtained from the measured CFs. Solid curves in Fig. 1a show the result of calculations performed with the FDTD technique. Experimental results are in a reasonable agreement with calculations. Strong dependence of the TPP lifetime on the angle of incidence and polarization of incoming light is determined by a quality factor of TPP resonance, which is governed by the Fresnel reflection law.



(a) (b)

Fig. 1. a) Measured (dots) and calculated (solid curves) dependence of TPP lifetime on angle of incidence for *s*- (black) and *p*- (red) polarized light. Inset: measured cross-correlation functions of laser pulses reflected from the sample at 45° for *s*- (black dots) and *p*- (red dots) polarization of incident radiation. Blue solid curve corresponds to the auto-correlation function of the incident pulse. b) Spectra of *s*- (black) and *p*- (red) polarized laser pulses reflected from the sample.

In summary, the direct experimental measurements of the Tamm plasmon-polariton lifetime were performed. The lifetime of the Tamm plasmon-polariton excited in a 1D photonic-crystal/metal-film structure was shown to vary from 20 fs for *p*-polarized light to 40 fs for *s*-polarized light at a 45° angle of incidence. Short lifetime and sharpness of resonance make TPP a good candidate for use in all-optical switches and modulators.

References

1. M. E. Sasin, R. P. Seisyan, M. A. Kaliteevski, S. Brand, R. A. Abram, J. M. Chamberlain, A. Yu. Egorov, A. P. Vasilev, V. S. Mikhrin, and A. V. Kavokin, "Tamm plasmon polaritons: Slow and spatially compact light", Appl. Phys. Lett. **92**, 251112 (2008).
2. B. I. Afinogenov, V. O. Bessonov, A. A. Nikulin, and A. A. Fedyanin, "Observation of hybrid state of Tamm and surface plasmon-polaritons in one-dimensional photonic crystals", Appl. Phys. Lett. **103**, 061112 (2013).
3. C. Symonds, G. Lheureux, J. P. Hugonin, J. J. Greffet, J. Laverdant, G. Brucoli, A. Lemaitre, P. Senellart, and J. Bellessa,"Confined Tamm plasmon lasers", Nano Lett. **13**, 3179 (2013).
4. R. Das, T. Srivastava, and R. Jha, "Tamm-plasmon and surface-plasmon hybrid-mode based refractometry in photonic bandgap structures", Opt. Lett. **39**, 896 (2014).
5. B. I. Afinogenov, V. O. Bessonov, and A. A. Fedyanin, "Second-harmonic generation enhancement in the presence of Tamm plasmon-polaritons", Opt. Lett. **39**, 6895 (2014).
6. P. Melentiev, A. Afanasiev, and V. Balykin, "Optical Tamm state on a femtosecond time scale", Phys. Rev. A **88**, 053841 (2013).