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Steps toward the experimental realization of surface plasmon polariton enhanced spontaneous parametric down-conversion

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ABSTRACT

The realization of efficient and miniature source of entangled photon pairs stills remains a challenge. In this work, we experimentally studied the possibility to enhance the process of spontaneous parametric down-conversion by surface plasmon polaritons. The details of the experimental setup will be discussed along with theoretical calculations of the enhancement factor.

1. Introduction

Efficient source of entangled photon pairs is essential for many quantum optical experiments and applications like quantum communication, quantum-key distribution, quantum computing, etc. [1,2]. Up to now, the most perspective source of entangled photon pairs is based on spontaneous parametric down-conversion (SPDC) – splitting of pump photons into signal and idler photons due to nonlinear interaction with matter. Most commonly, the SPDC takes place in a bulk crystal, however, the practical availability is limited by the low efficiency of SPDC (only around 10^{-12}) and large footprint of the crystal (several millimeters) [3–5]. To overcome the problem of the low efficiency, the process of SPDC have been studied in nonlinear periodically-poled waveguides by many research groups and efficiencies up to 10^{-6} have been reported [6–10]. However, the problem of large footprint still remains as a limitation of practical usability in miniature devices.

An idea to use the field enhancement of surface plasmon polaritons (SPPs) to boost the efficiency of SPDC was theoretically studied in Refs. [11,12] and enhancements, also accessible in miniature sources, up to 40×10^3 were predicted. For the proof of principle, the SPP-enhanced SPDC were studied in the structure similar to Kretschmann configuration (see Fig. 1), so splitting pump photons into two SPP modes (denoted by β_s and β_i in Fig. 1) instead to photonic modes becomes possible if phase-matching conditions (see Ref. [11])

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}, \tag{1}$$

$$k_p(\lambda_p, \theta_p) = \beta_s(\lambda_s) + \beta_i(\lambda_i), \tag{2}$$

are fulfilled, where λ_p, λ_s and λ_i denote the wavelength of the pump, signal and idler, respectively, $k_p = 2\pi n_p \sin\theta_p/\lambda_p$ is the tangential wavevector component of the pump beam, θ_p is the angle of incidence of the pump beam inside the prism, n_p is the refractive index of the prism, β_s and β_i are the propagation constants of the signal and idler SPP modes, respectively. The enhancement of SPDC follows from the field enhancements of two participating plasmonic modes and the total enhancement of SPDC is given by

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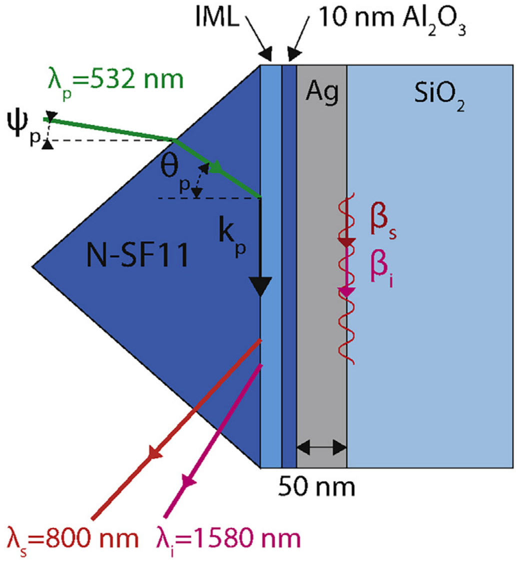

Fig. 1. The structure for SPP-enhanced SPDC: N-SF11 prism, index-matching liquid (IML), Al_2O_3 layer, silver layer and single crystal alpha quartz. The angle of incidence of the pump laser ($\lambda_p = 532$ nm) is Ψ_p outside the prism and θ_p inside the prism. The propagation constants of signal ($\lambda_s = 800$ nm) and idler ($\lambda_i = 1580$ nm) plasmons are β_s and β_i, respectively.

$$\Upsilon = \eta_p^2 \eta_s^2 \eta_i^2, \tag{3}$$

where η_p, η_s and η_i denote the field enhancement factors of the pump, signal and idler, respectively [11]. After propagation, the signal and idler plasmons leak back to the prism as photons.

For an efficient generation of the signal of the SPP-enhanced SPDC four main prerequisites were listed in Ref. [12]:

1. Plasmonic field enhancement must be available. It was shown, that simple enhancement formula given by Eq. (3) describes the enhancement of SPDC really well, provided that the beam width (≈1 mm) and the SPP resonances (≈0.1°) are not too narrow (also the case in this work), otherwise, the enhancement factor is reduced due to the fact that only a small part of participating vacuum fluctuation modes are in enhanced plasmonic mode and narrow laser beams interact inefficiently with very narrow plasmonic resonances.
2. Fulfilling phase-matching conditions are really important as in the case of conventional SPDC. In the latter case, birefringence or periodical poling is typically used to achieve perfect phase-matching. In the case of SPP-enhanced SPDC, however, the perfect phase-matching is achievable only by adjusting the angle of incidence of the pump beam. The main limitation of perfectly phase-matched coherent buildup length is the presence of inherent losses of the SPP mode.
3. As the signal of the SPDC is generated in the SPP mode, the outcoupling of plasmons back to the prism as photons must be efficient, otherwise, the generated signal and idler plasmons are absorbed in the metal film.
4. The interaction of SPP mode with nonlinear medium must be efficient, as the SPP mode is only partially in nonlinear medium (the metal is linear).

The goal of this work is the experimental realization of SPP-enhanced SPDC in the structure shown in Fig. 1. To do that, goniometric measurement setup with lock-in amplification was designed. To the best of our knowledge, it is the first experimental attempt to plasmonically enhance SPDC.

2. Experimental setup

2.1. Structure

The structure for the realization of SPP-enhanced SPDC is shown in Fig. 1. First, polished X-cut single crystal quartz substrate ($10 \times 10 \times 0.5$ mm^3) was bought from PI-KEM Ltd. It acts as a nonlinear crystal (second-order susceptibility $\chi^{(2)}_{xxx} = 0.6$ pm/V) and is selected due to relatively small refractive index (≈1.55) in comparison to the other commercially available nonlinear crystals [13]. Next, approximately 50 nm thick silver film was deposited on one side of the quartz crystal and subsequently covered with approximately 10 nm thick aluminum oxide layer in order to protect the silver surface. The deposition was done by AJA International ultra-high vacuum magnetron sputtering system at room temperature. The silver film was deposited using 2 inch target, 3 mTorr argon pressure, 55 W direct current power, 10 W biasing RF (radio frequency) power at the sample (to make the silver surface smoother) and the deposition time was 300 s. The aluminum oxide was deposited using 3 inch target, 3 mTorr argon pressure, 150 W