Planar plasmonic optics: from basic elements to quantum generator

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Abstract. The key advantage of plasmonics is in pushing our control of light down to the nanoscale. It is possible to envision lithographically fabricated plasmonic devices for future quantum information processing or cryptography at the nanoscale in two dimensions. Here we demonstrate the development of the basic elements of planar plasmonic optics: plasmonic optics media, focusing and reflecting plasmonic elements, plasmonic interferometer, plasmonic autocorrelator and planar plasmonic quantum generator.

1. Introduction
Plasmon optics, like all other types of optics (photon, electron, atomic) - solves the problem of controlling the appropriate types of waves. For effective control of plasmon waves, it is necessary to create appropriate control elements: the medium in which the wave (surface plasmon – polaritons, SPP) propagates, focusing elements (lenses, mirrors), beam splitter, interferometers, detector and SPP wave generator. We report development of the basic elements of plasmon optics, including:

- Propagation medium for SPP waves (single-crystal metal surfaces with a large propagation length of SPP waves);
- Nanolocalized sources of SPP waves in the visible and ultra-violet wavelength region;
- mirrors for SPP waves;
- SPP interferometer;
- SPP wave detector;
- Plasmonic nanolaser.

Figure 1. Optical microscopy of SPP waves: (a) optical image of a Ag film surface with nanostructures created by an ion-beam lithography, (b) optical image of Ag film surface when SPP excited by a laser radiation, (c) the cut image of figure 1b along the SPP propagation direction; the dotted curve - the approximation by exponential curve with the characteristic decay length of 93 μm [1].
2. Propagation medium

The choice of material for creating plasmonic nanostructures is decisive in achieving its best properties. We show [1] that the newest developed method of epitaxial growth of silver films makes it possible to realize in nanoplasmonics a propagation medium for SPP with losses corresponding to the theoretical values. The SPP on the surface of such nanofilms (780 nm) is characterized by a record long propagation length equals to 200 μm. This value is more than twice larger than the best known experimental results. Fig. 1 show the optical image of a Ag film surface with a nanostructures created by a focused-ion-beam lithography. The nanostructures used to excite SPP and to measure SPP propagation length on the Ag surface (figure 1).

3. Nanolocalized sources of SPP waves

We proposed and developed a new element of nanoplasmonics - a hybrid nanostructure: Split - Hole Resonator (SHR) [2], which has the following unique properties: (1) record high efficiency of third harmonic generation and multiphoton luminescence [2-4]; (2) a record high sensitivity to radiation polarization, with an extinction coefficient of the order of $4 \times 10^4$ [5]. We have shown that the presence of a strong localized plasmon resonance of the SHR nanostructure and the use of a femto laser pulse (two periods of light wave oscillations) allows the realization of an effective nanolocalized light source of the 2-nd and 3-rd harmonics in ultra-violet (UV) spectral region [4]. The amplitude of the near-field radiation at the frequency of the 3-rd harmonic is 0.6% of the field amplitude at the fundamental frequency, which is currently the maximum achievable value.

4. Focusing of SPP waves

Reflection and focusing of the SPP waves opens a unique possibility of controlling the propagation characteristics of the SPP waves. A method for controlling the SPP wave propagation was proposed and implemented, using SPP wave reflection from a "SPP wave mirror", created in the form of a nanoslit located on the surface of a metal nanofilm. The realization of reflection by means of a "SPP wave mirror" allows not only the control of propagation direction of the SPP wave, but also to focus it in a diffraction-limited spot [6].

Due to losses in the metal, the propagation length of the SPP wave on the surface of the metal is severely limited and this is a great limitation for numerous SPP applications. We have shown that the focusing of SPP allows a significant increase in the effective propagation length of SPP wave. A significant increase in the propagation length of the SPP wave makes it possible to realize a high-speed data transmission line at a distance of the order of 1 mm at a wavelength of 780 nm. It is shown that the information transfer rate of this transmission line is as high as 3.5 THz. The large propagation length of the SPP wave and high information transfer rate open up new possibilities for using SPP waves in information transfer applications [7].

5. SPP wave detector

The SPP wave detector is based on the nanostructuring of a metal surface. A technique for detecting SPP waves by its scattering on nanoparticles (nano-grooves) created by the method of ion lithography on a metal surface is developed [8]. The scattering cross section greatly decreases with the particle size, while the absorption is linearly dependent on the volume. Thus, the scattering is more sensitive and preferable for SPP detectors. The method of scattering detection is applicable to extremely clean surfaces of high optical quality. The scheme of the SPP wave detection on the surface of single-crystal gold or silver films based on nanogrooves was realized. Nanogrooves make it possible to "visualize" the process of propagation of a SPP wave on the surface of a metallic nanofilm. The use of nanogrooves as local detectors allows us to determine the propagation length of a SPP wave. The obtained value of the propagation length of the SPP wave is in good agreement with the measurement data obtained with the help of a SPP interferometer.
6. SPP interferometer

In experiments on nanoplasmonics, it would be ideal to measure the duration of a laser pulse directly in the object plane of the sample. We present results of our experimental investigations on the creation of a SPP tilted slit–groove (TSG) interferometer [9], which was prepared in a metal gold film. The possibility of monitoring the pulse duration in the interval from 6 to 50 fs is shown.

Figure 2. Scheme of SPP interferometer [9].

Figure 2 shows the schematic image of a TSG interferometer that was prepared in a gold film by a slit and a groove tilted at a certain angle to the slit. When measuring the laser pulse duration, the interferometer was illuminated by the laser beam perpendicularly to the film plane. The scattering of the laser light by the groove leads to the excitation of a SPP wave with wave vector $k_{sp}$, which is perpendicular to the groove. The SPP wave propagating from the groove in the direction toward the slit is partially scattered by the slit and creates a near field in the region of the nanoslit. Because of the occurrence of angle between the slit and the groove, the distance traveled by the SPP wave from the groove to the slit varies linearly along the slit axis. This leads to a dependence of the field amplitude on coordinate and to a similar dependence of its phase. The occurrence of the angle between the slit and the groove gives rise to interference of the near fields of the laser radiation in the slit. The SPP interferogram obtained by excitation of SPP interferometer with laser radiation is shown on figure 3.

Figure 3. (a) SEM image of SPP interferometer, (b) SPP wave interferogram obtained by excitation of an interferometer with laser radiation of a wavelength 800 nm [9].
7. The plasmonic nanolaser

We design [10] a planar plasmonic nanolaser, extending the idea and implementation of plasmonic lasers reported in [11]. It is a planar waveguide made of a layer of liquid gain medium deposited on a plasmonic crystal (see figure 4). The plasmonic crystal is formed by an array of nanoholes (175 nm diameter and a pitch of 565 nm) created in a 100-nm-thick silver film deposited onto a quartz substrate. Dye molecules are optimal for plasmonic lasers because the dye molecules are capable of nearly 100% yield and allow for the creation of an optically homogeneous medium with high gain. We use a liquid gain medium: solution of dye molecules R101. The use of a liquid gain medium offers the advantages over a solid gain medium by fixing the bleaching problem. Also, the employment of microfluidics make plasmonic intracavity spectroscopy suitable for the lab-on-chip technology.

![Figure 4. Scheme of plasmonic nanolaser: Planar waveguide made of a liquid gain medium layer (a solution of R101 dye in dimethyl sulfoxide (DMSO)) deposited on a plasmonic crystal [10].](image)

The lasing occurs at pumping intensities above 500 kW/cm. The spectrum of the plasmonic laser for two values of pumping are shown in figure 5. At intensities below 500 kW/cm², the spectral contour is very similar to that of usual R101 dye luminescence. However, at higher pumping intensities, the luminescence contour changes dramatically, and a very narrow spectral line with the half-width of 1.7 nm emerges at 628 nm. Such a narrow line width indicates that we deal with lasing.

![Figure 5. (a) The spectrum of dye luminescence in the quartz/silver/DMSO/quartz system without nanoholes; (b) the luminescence spectrum of the plasmonic laser. The insets show electronic microscope images of the samples [10].](image)
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