PROCEEDINGS OF THE INTERNATIONAL CONFERENCE
NANOMATERIALS: APPLICATIONS AND PROPERTIES
Vol. **3** No 2, 02NAESF08(3pp) (2014)

Surface Plasmon-Polariton in X – Shaped Waveguides

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(Received 15 July 2014; published online 29 August 2014)

A method of projection optical lithography to form X-shaped waveguides surface plasmon polaritons, (SPP) is proposed in current paper. A physical system based on point dipole approximation is taken as a theoretical basis for modeling of the SPP emergence processes. The possibility to control spreading of the SPP depending on the phase of the excitation of the optical signal is investigated.

Keywords: Optical lithography, Surface plasmon polariton, Optical signal.

PACS number: 73.20.Mf

1. INTRODUCTION

To date, different approaches to achieve efficient excitation of surface plasmon polaritons (PPP) [1-4] and geometrically limited distribution channels are proposed [5, 6]. Issues of making the dielectric inhomogeneous waveguide, which provide a simple and cost-effective way to achieve strong lateral retention SPP and implementation of integrated components are in a state of continuous investigations. Particular interests represent works on implementing the waveguide, creating the ability to control light and transmit the signal.

An optimal method to obtain nano scale waveguides based on Au or Ag films is proposed and SPP propagation in such waveguides using a laser with a wavelength of 632.8 nm as the source of the optical signal is observed and the possibility to control the signal is studied in this paper.

2. THEORETICAL PART

Processes arising in the SPP on the surface of nanosized metal film can be described by the model of the physical system based on point dipole approximation [7]. This method has some limitations, but allows circumventing of problems associated with energy dissipation on the interface metal film - dielectric basis and takes into account only the energy transfer between particles.

Nanostructured metal film surface can be represented as a chain of strongly interacting atoms (Fig. 1). The light is directed to the first atom of the chain, the rest is pre-irradiated by scattering energy. The polarization of the external field can be either *S* or *R*. Thus Maxwell's equations and calculations to carry out with the help of the Green's function can be used to describe such a physical system. The electric field in such a structure can be determined from the Lipmann-Schwinger equation [8]:

$$\mathrm{E}(\mathrm{r}) = \mathrm{E}^0(r) + k_0^2 \sum_{i=1}^{N} \int_{V_i} \hat{G}(r,r')(\varepsilon_3 - 1)E(r')dr' \qquad (2.1)$$

where E_0 – external electric field at the starting point, k_0 – ballistic wave vector, N – total number of particles in the chain; V_i – volume occupied by the particle with number i; ε_3 – dielectric constant of Au.

Light propagation without particles is described by Green tensor G(r, r′) [9]. In the dipole approximation, each nanoparticle is considered as a dipole reflector with a dipole moment, which can be obtained by the following equation solution [10,11]:

$$\begin{aligned}\mathrm{p}_1 &= \hat{\alpha}_1 E^0(r_1) + \frac{k_0^2}{\varepsilon_0}\hat{\alpha}_1 \hat{G}^s(r_1,r_1)p_1 + \\ &+ \frac{k_0^2}{\varepsilon_0}\sum_{j\neq 1}^{N}[\hat{G}^0(r_1,r_j) + \hat{G}^s(r_1,r_j)]p_j\end{aligned} \qquad (2.2)$$

$$\begin{aligned}\mathrm{p}_1 &= \frac{k_0^2}{\varepsilon_0}\hat{\alpha}_i \hat{G}^s(r_i,r_i)p_i + \\ &+ \frac{k_0^2}{\varepsilon_0}\sum_{j\neq 1}^{N}\hat{\alpha}_i[\hat{G}^0(r_i,r_j) + \hat{G}^s(r_i,r_j)]p_j \\ &j = 2 \ldots \mathrm{N}\end{aligned} \qquad (2.3)$$

where $r_i = (x_i, y_i, z_i)$ – radius vector of i particle; ε_0 - dielectric constant; α_i - dimensionless tensor of i particle.

Given the identity of the spherical particles with half axis h_x, h_y, h_z and parallel to the axes, the tensor polarization in the long-wave approximation is [12,13]:

$$\hat{\alpha} = (\alpha_x \hat{x}\hat{x} + \alpha_y \hat{y}\hat{y} + \alpha_z \hat{z}\hat{z}) \qquad (2.4)$$

$$\alpha_\tau = \frac{\varepsilon_0 V(\varepsilon_3 - 1)}{1 + (\varepsilon_3 - 1)m_\tau},\ \tau = \mathrm{x, y, z.} \qquad (2.5)$$

where $V = 4\pi h_x h_y h_z / 3$ – particle volume, m_x,m_y,m_z - rate of depolarization.

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Because nanoparticles are based on a dielectric basis, then the Green's tensor is $G_0(r, r')$ and $G_s(r, r')$.

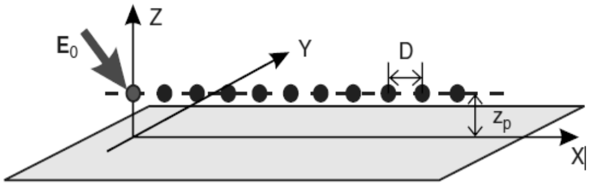

Fig. 1 – Schematic representation of the system: long linear chain of identical spheroidal particles of gold

Component $G_0(r, r')$ determines the value of a constant electric field, and $G_s(r, r')$ represents a field that is scattered by the metal-dielectric interface.

Consequently, the electric field on the metal surface can be described by the equation:

$$E(r) = k_0^2 \sum_{i=1}^{N} [\hat{G}^0(r, r_i) + \hat{G}^S(r, r_i)] p_i \qquad (2.6)$$

Tensor $G_0(r, r')$ can be solved analytically [14]. In general, given that the particles in the chain are close to the interface and have a size much smaller than the wavelength, it greatly simplifies the numerical method. In particular, if the distance between the source and the observation point is less than 20λ - Green's tensor has the exact value, including all methods of dispersion and approximated only part of the plasmon. Numerical simulations provide the accuracy of this method of calculation about (5-7) %.

3. WAVEGUIDE FORMATION METHOD

The method of dual energy polymerization [15] was used to form these waveguides. Negative organic-inorganic hybrid photoresist was used to form the waveguides and a femtosecond laser with a wavelength of 515 nm and pulse duration of 250 fs was applied to expose it. Given that the femtosecond laser is quite expensive and sensitive to the environment; a phased optical photolithography method was proposed to form nanoscale waveguides.

The scheme of the process is shown in Figure 2. For this system, a mask reduced by 10 times with respect to the template is needed.

The next step is the process of reducing the size of the waveguide to the scale 1 : 100 and the creation of a prototype. The process of prototype formation on gold is similar to the mask formation on silver, but in this case, the negative brand of polymer mr-NIL 6000.1E (Germany), a light-emitting diode light source with a wavelength of 365 nm and a system of lenses were applied. The resulting X-shaped waveguide is shown in Figure 3a.

The SPP excitation comes from the laser with a wavelength of 800 nm. A distribution plazmon in the waveguide is obtained by excitation of this waveguide in the middle. By changing the phase of the laser it can be possible to change a SPP direction, as is shown in Fig. 3b. Fourier image (Fig. 3b) confirms that SPP occurs in the proposed X-shaped waveguide and it can

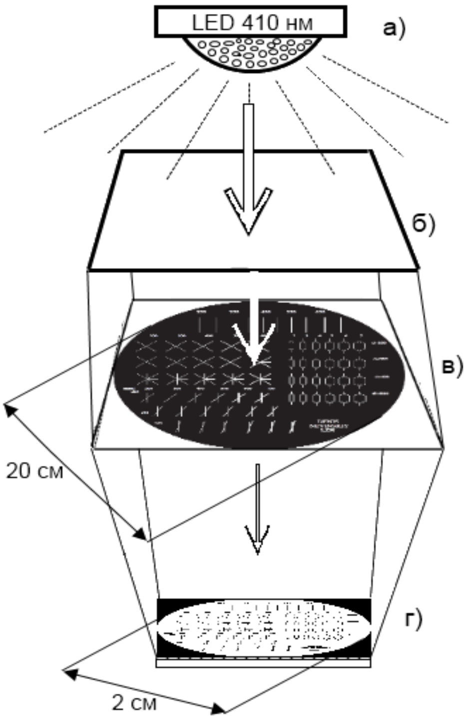

Fig. 2 – The scheme of waveguides image exposure in the 1:10 scale: a) - light-emitting diode with a wavelength of 410 nm; b) - the lens; c) the 20 cm template diameter; g) - obtained mask with a diameter of 2 cm

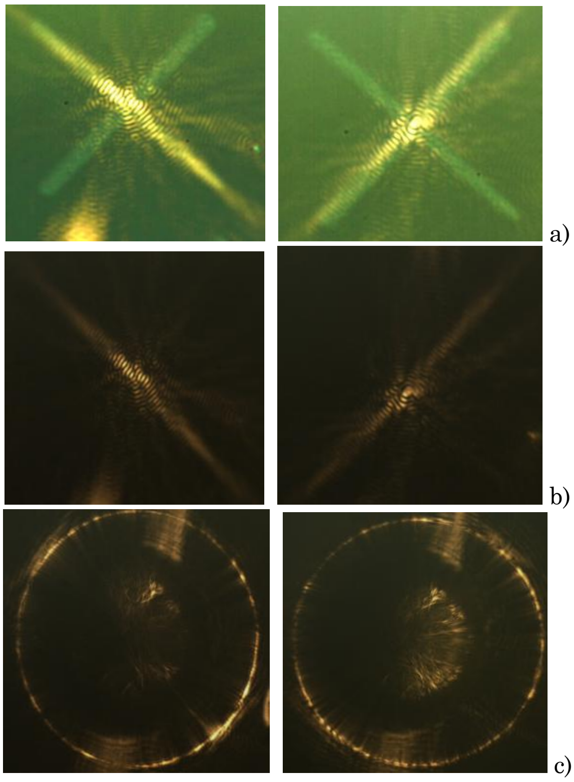

Fig. 3 – Distribution of the SPP in the X-shaped waveguide:
a) - waveguide image obtained with the LR microscope [16];
b) - SPP propagation in the waveguide, by changing the phase of the wave;
c) - Fourier image, confirming that the SPP occurs in proposed waveguide.

be controlled the direction of its passing (distribution) along one or other shoulder of X - shaped waveguide.

These properties of the structure give ample opportunities to create both passive elements to control light (e.g., filters) and active components nanoschemes, sensors, etc.

4. CONCLUSIONS

The use of the proposed technology makes it possible to simplify the process and reduce the cost of obtaining the dielectric inhomogeneous nanoscale waveguides for the emergence of the SPP. Samples obtained by optical photolithography show clear lines, steep walls of polymerised or exposed photoresist, and conductive channels of various configurations can be formed. The method proposed can completely replace the two-photon polymerization. With this technology it is possible to create optical elements with predetermined optical properties. Propagation of SPP in X-shaped waveguides is tested and presented. Current results will be used to create compact elements for optical information processing, as well as a new class of sensors for information and communication devices.

AKNOWLEDGEMENTS

Special thanks to the staff of the department of nanotechnology Laser Zentrum Hannover (LZH), Germany, for the opportunity to conduct experiments.

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