Peculiarities of prismatic input of narrow-band radiation into Ag-ion diffusion waveguide

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Abstract. The peculiarities of prism coupling elements input and output of narrow-band radiation into ion diffusion waveguide are researched. Gradient waveguide with a thickness of 1.67 µm was formed by ion exchange in K8 glass. The output signal intensity dependence on the input and output angles of incidence radiation was measured by developed automatic hardware-software system based on synchronous detection method to improve the signal-to-noise ratio. It was shown the maximum of output signal is reached at equal input and output angles.

1. Introduction
Nowadays there is a growing interest in materials with nanoparticles (NPs) of noble metals due to their unique optical properties [1]. When metal NPs are irradiated with light, the electromagnetic field energy transforms into the energy of collective vibrations of conduction electrons at the metal-insulator interface — a phenomenon is called the localized surface plasmon resonance (LSPR). Glasses with silver NPs on the surface are perspective structures as optical sensors for biological and medical applications because of the high sensitivity of the LSPR spectral position to the external environment refractive index [2, 3].

Traditionally, surface plasmon resonance excitation in thin metal (gold) films is used to detect biological interactions in the Kretschmann configuration. This method implementing devices are quite complex, expensive, requiring precision angular measurements. In the same time, devices based on localized plasmon resonance in nanoparticles, located on the surface of the waveguides, can significantly simplify this approach. The physical principle is based in this case on the interactions between waveguide mode and the plasmon mode, sensitive to the dielectric constant of the environment. So, it allows one to avoid complex angular measurements, significantly miniaturize the device, making it accessible for mass production [4].

We used in our scheme (figure 2) triangular prisms located on the diffusion waveguide layer surface to excite and detect the waveguide mode [5]. Silver nanoparticles synthesized in the working area of the sensor influence on the optical response by changing the dissipated energy of the waveguide mode.

In our work we study the K8 glass substrates as large as 1 mm thick with diffusion waveguide and synthesized silver NPs on the surface [6]. Our preliminary studies show that silver nanoparticles do not have sufficient adhesion to glass and can be partially washed off by liquid. One way to solve this problem is to coat the glass surface with a thin polymer layer. We used biocompatible polymer polyamide-6 (PA-6), which is promising for further biological applications [7].
In this paper we used prism coupling element to excite localized plasmon resonance by narrow-band radiation in silver nanoparticles on top of diffusion waveguide. Particles on the glass surface were observed by scanning electron microscopy (SEM). Low-intensity optical signals were measured by the synchronous detection method in order to improve the signal-to-noise ratio. The purpose of the present work was to study the features of measuring the output signal intensity dependence on the angle of incidence and output angles of narrow-wave radiation.

2. Experiment

2.1. Synthesis and characterization of silver nanoparticles

Silver NPs on the K8 glass surface were synthesized by the ion exchange technique (350°C) followed by reduction in water vapor (325°C) [8]. This temperature conditions are optimal to get the narrowest spectral LSPR peak. During the ion exchange process, a diffusion waveguide with 1.67 µm thickness is formed in the subsurface region of the glass [9]. Images of glasses with nanoparticles were obtained using SEM JSM-7001F (Jeol, Japan) in the mode of secondary electrons without any coatings to drain the charge. Figure 1(a) shows a typical electron microscopic image of the synthesized NPs. The image processing made by ImageJ free software allowed to draw a histogram of NPs size distribution. Based on this histogram (figure 1(b)) it was determined most particles have size in the range from 20 to 30 nm. The filling factor is about 6%.

Using approximation of the structure absorption spectrum by the Lorenz method, the position of the resonance peak was determined to be 451 nm (figure 1(c)). This wavelength position corresponds to the LSPR range of silver nanoparticles with average size as large as 25 nm and is in a good agreement with Mie theory for spherical nanoparticles.

![Figure 1](image1.png)

**Figure 1.** Characterization of K8 glass surface with Ag NPs: (a) SEM image of synthesized NPs; (b) histogram of NPs size distribution; (c) absorption peak of Ag NPs.

2.2. Polyamide-6 coating

By dissolving of PA-6 in 85% formic acid the solutions with concentrations of 1, 1.2, 1.5, and 3% were prepared. Thin PA-6 films with different thicknesses were obtained over glass substrates with silver NPs by centrifugation technique. Rotation speed was 4000 rpm. Coating time was 60 seconds.

Also Si substrates were coated with the same solution concentrations of PA-6 for comparative measurements by atomic force microscopy (AFM). Thickness control measurements were made by atomic force microscope Dimension 3100 (Veeco, USA). Substrates were scratched, then...
scratch profile was written by AFM probe to measure the thicknesses of the films. Measurement results are presented in table 1.

| Concentration, weight % | Thickness, nm |
|-------------------------|--------------|
| 1                       | 20 ± 5       |
| 1.2                     | 40 ± 5       |
| 1.5                     | 120 ± 5      |
| 3                       | 625 ± 5      |

2.3. Prismatic input and output of narrow-band radiation
A series of experiments were performed to input and output radiation from a narrow-band source into a diffusion waveguide using prismatic coupling elements. For this purpose, a hardware-software complex was assembled to automatic measure the output signal intensity dependence on the input and output angles of incidence radiation (figure 2). A semiconductor laser diode (405 nm) was used as a narrow-band radiation source. The wavelength of the incident radiation can be located on any branch of the spectrum, so as not to lead to an uncertainty in the offset of the output signal, as it would if it corresponded to the symmetrical maximum of the spectrum. Two sapphire prisms were installed with a small air gap on the surface of the glass freed from nanoparticles. Low-intensity signals were measured by the synchronous detection method (Lock-in nanovoltmeter type 232 (Poland)) in order to improve the signal-to-noise ratio.

Sequential scanning was performed at angles from 45 to 90 degrees of the laser and the photodiode. The angles step of 1 degree was realized by PC controlled servomotors. Such automated procedure allowed us to obtain intensity distribution maps of the output signal in dependence on the angle of incidence radiation and the angle of the output signal detection. The height position of the sample was chosen so the radiation of the source fell on the prism-waveguide interface. Measurement results are presented on figure 3 as a dependence of the signal intensity
Figure 3. Intensity dependence on source and detection angles.

distribution of input and output angles. The maximum signal intensity is observed when the input angle is equal to the detector angle. Wide angular intensity distribution is explained by the angle diagram of the laser diode and reflections in prisms. The system response to angle change indicates that the light passing through the prism-waveguide-prism system, because the experimental setup configuration excludes other paths of radiation to the detector. Angles outside the range shown in figure 3 were not considered due to light did not reach the prism-waveguide interface.

3. Conclusion
Thus the possibility of a prismatic input of radiation into ion diffusion waveguide formed in glass substrate was demonstrated. The dependence of the output signal intensity on the incidence light angle and the detector angle was studied. It was shown the maximum output of radiation is provided when these angles are equal. Work results indicates the possibility of prismatic radiation input into the ion-exchange waveguide in glasses with NPs on the surface for biosensor applications.

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