

The field enhancement and optical sensing in the surface photonic chrystal

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New dielectric metamaterial based on the Bragg filter comprising ten dielectric bilayers was investigated. Each bilayer is the thin films of silicone dioxide (SiO_2) and another film of zirconium dioxide (ZrO_2). The surface of the multilayer film is profiled. It has a form of periodic system of rectangles separated by the open gaps. We use the computer simulation as well as analytical solution to find the reflectance of the multilayer as a function of the wavelength and electromagnetic (em) field distribution. The multilayer system reveals the enhancement of em fields at the surface. The considered Bragg filter was modified by Raman-active structure made of gold nanoparticles with chemically attached 3,3'-thio-bis (6-nitrobenzoic acid) — (TNB). The high Surface Enhanced Raman Scattering (SERS) signal was detected.

1 INTRODUCTION

The optical response of metal nanostructures and its resonance effects, which are associated with surface plasmons (SP) excitation, have attracted significant attention due to exciting practical applications in optical filters [1], subwavelength optical waveguides[2], SERS[3] et al. SERS being the most powerful analytic instrument for the effective chemical and biological analysis potentially results in the appearance of the high technological optical sensors [9]. Such sensors are based on the generation of different plasmon modes in the metal surfaces and further Raman scattering of these plasmons on molecules. The basic element of the detecting system is the SERS substrate, which typically is a matrix of the metallic inclusions fabricated from Au or Ag. The quality as well as absolute value of Raman signal strongly depend on the arrangement, shape, size and chemical composition of the substrate structure. Therefore the substrates based on dielectric resonators could decrease internal absorption and increase the efficiency of the sensors [4,5].

The inclusions can be considered as nanoscaled antennas, which concentrate the incident radiation. The collective electromagnetic (em) field is excited as result of the interaction of the incident light with metallic and dielectric inclusions. The em field oscillations have several resonance frequencies and the local field is substantially enhanced with respect to the incident field. In this paper we investigate SERS active dielectric substrate fabricated from thin-film multilayer.

1.1 Bragg filter

Let us consider a thin-film multilayer comprising 10 bilayers characterized by indices of refraction n_1 , n_2 , and thicknesses d_1 , d_2 , placed on semi-infinite substrate with refractive index n_0 . The reflectance of the multilayer can be simply analytically found from the Fresnel equations [6]. Figure 1 presents the calculated and measured reflectance spectra of the multilayer comprising 10 bilayers of zirconium dioxide (ZrO_2) and silicium dioxide (SiO_2) placed on aluminium substrate. The summarized thickness of the multilayer $\approx 2.6 \mu\text{m}$. Here $n_1 = n_{\text{ZrO}_2}$ is the refractive index of zirconium dioxide (ZrO_2), $n_2 = n_{\text{SiO}_2}$ is the refractive index of silicium dioxide (SiO_2). The refractive index for aluminum was taken from [7]. The analytical reflectance shows the almost complete blockage of the incident wave at free-space wavelengths in the neighborhood of 600–820 nm. The experimental reflectance has a smaller amplitude due to the natural roughness and an absorption [11].

1.2 Surface periodic structure

The surface of the multilayer comprising 10 bilayers of silicone dioxide (SiO_2) and zirconium dioxide

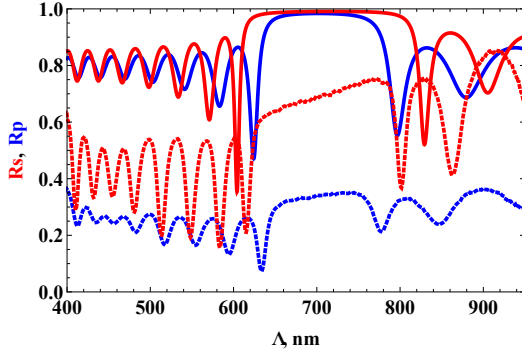


Figure 1: The calculated (solid lines) and measured (dotted) reflectance of the multilayer as a function of the free-space wavelength λ for angle of incidence $\phi = 45^\circ$ for s- (red) and p- (blue) polarized waves. The other parameters $d_1 = 97$ nm, $d_2 = 129$ nm, $n_{Zr} = 2.035$, $n_{Si} = 1.45376$.

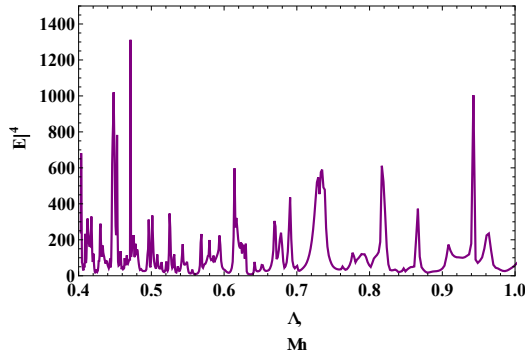


Figure 2: The maximum surface electric field $|E/E_0|^4$ as a function of free-space wavelength for angle of incidence $\phi = 45^\circ$ for p- polarization. The geometrical parameters were taken from the experiment.

(ZrO_2) was modified by FIB-assisted modification so to create a periodic system of rectangle structures with width $1 \mu m$ segregated by the gaps with width 100 nm and depth $\approx 1.5 \mu m$. Our computer simulations show the surface structure result in the em field $G = |E/E_0|^4 \approx 10^3$ enhancement of due to excitation of dielectric resonances (Fig. 2). The morphology of the surface nanostructures was studied by scanning electron microscopy (SEM) using a Quanta microscope (FEI) with resolution near 5 nm (Fig. 3). The periodic surface structures with summarized dimensional size $500 \times 250 \mu m$ were obtained by systematic etching with beam current 790 pA.

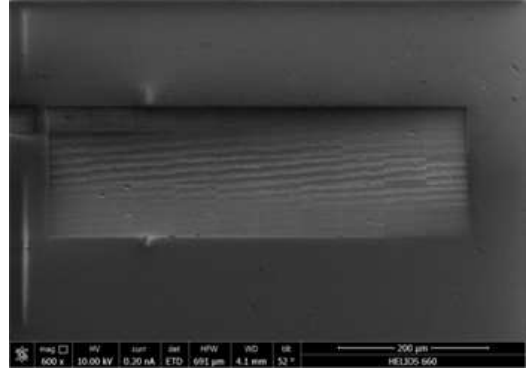


Figure 3: SEM images of the surface periodic structure.

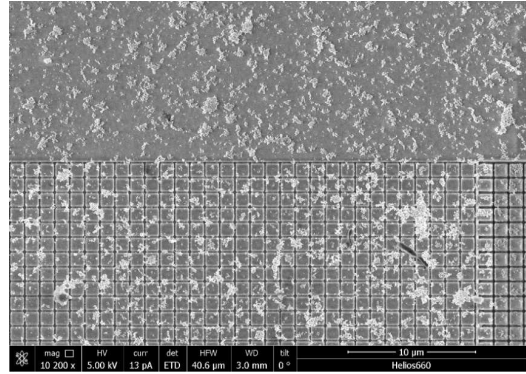


Figure 4: SEM images of surface periodic structure with immobilized Au-NP.

The gold nanoparticles (Au-NP) with average size 56 nm were prepared by citrate method [8]. For the preparation of SERS active particles, Au-NPs were modified by 3,3-thio-bis (6-nitrobenzoic acid) — (TNB) [9]. Au-NPs were adsorbed onto the surface periodic structure after deposition of polycation (poly(diallyldimethylammonium chloride)) according to the procedure described in the article [10] (Fig. 4)

1.3 SERS spectra

A Raman spectrometer WITec with continuous-wave laser-785 (< 250 mW) was used for the collection of spectra using an excitation wavelength of 785 nm. The excitation was performed in an epi configuration through a $100\times$ objective ($NA = 0.9$) on a microscope 1338 cm^{-1} . Raman scattering NO_2 band of thio 6-nitrobenzoic acid was used to investigate the SERS signal. The intensity distribution in the choosen band at the surface struc-

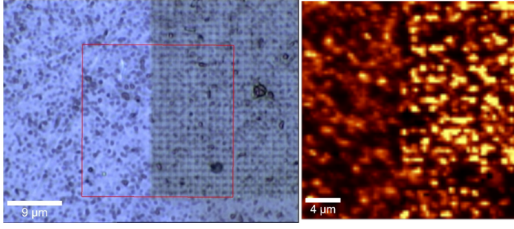


Figure 5: The optical mapping of the intensity distribution for Raman band 1338 cm^{-1} . The parameters of mapping: scan dimensions $25\text{ mkm} \times 25\text{ mkm}$, step of scanning $\approx 0.33\text{ }\mu\text{m}$. The excitation was performed in an epi configuration through a 100X objective (NA = 0.9) on a microscope WITec.

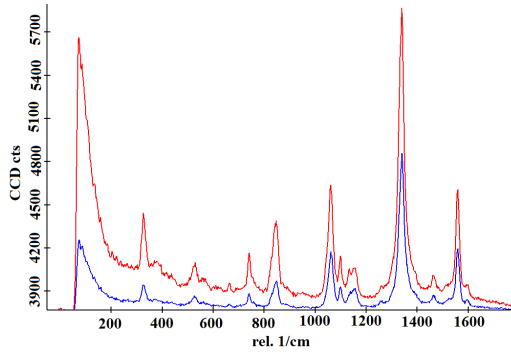


Figure 6: The intensity field distribution for band 1338 cm^{-1} . Red line corresponds to surface structure, blue line — neighboring region.

ture was compared with the intensity distribution at the neighboring area near the structure. The optical mapping of the intensity distribution for band 1338 cm^{-1} is shown in Fig. 5. We demonstrate huge enhancement of the intensity distribution in the surface structure (red line) with respect to neighboring region (blue line) Fig. 5, 6.

It should be noted that Fig. 6 demonstrates the relative value of intensity excluding the detailed accounting the density of particles in the surface.

1.4 Discussion

The dielectric metamaterial fabricated from thin-film multilayer comprising 10 bilayers of silicone dioxide (SiO_2) and zirconium dioxide (ZrO_2) placed on aluminium substrate was investigated. The multilayer behaves as a good Bragg filter showing the almost complete blockage of an incident wave at free-space wavelengths in the neighborhood of

$600\text{--}820\text{ nm}$. The modified multilayer with cavities exhibits the enhancement of the em field in the surface structure due to excitation of dielectric resonances. The hot spots are localized at the face side of the surface. The SERS signal, characterized by factor G reaches the value $G = |E/E_0|^4 = 10^3$. The results of our analytical and numerical calculations are in a good agreement with the experimental results. The SERS signal intensity from TNB is much enhanced in the case of modified multilayer with gold nanoparticles that are immobilized on its surface. We suggest using the proposed metamaterial as a core of the high sensitive optical sensing device. The resonance frequencies can be tuned by variation of the shape of the surface.

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