METASURFACE BASED NANOBIOSENSORS: comparative analysis of all-dielectric, metal-dielectric and graphene metasurface model structures

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INTRODUCTION

The development of innovative nanobiosensors of various designs for numerous biomedical applications is one of the fastest-growing areas in modern nanoscience and nanotechnology. Nanobiophysics focuses on studying the physical effects and mechanisms that provide sensitivity in sensory structures to biologically significant or medical diagnostic parameters of biological samples. Among the promising new materials used in biosensors as sensing elements, metasurfaces exhibit unique optical and electronic properties along with high tunability, allowing the precise control over the sensors working characteristics. Based on our previous experimental findings from microwave dielectrometry measurements and recent numerical modeling results, we proposed several model sensor structures based on metasurfaces with different designs for potential biomedical applications [1-4].

In this report, we present a comparative analysis of the physical characteristics and application prospects of the biosensors developed, which are based on all-dielectric [2], metal-dielectric [3], and graphene strips containing [3] metasurfaces.

METHODS

In our study, performed using COMSOL software, we conducted computational modeling of the design and operational parameters of the metasurfaces with different compositions [2-4]. We also tested the applicability of the biosensors to determine the concentrations of biologically significant proteins, such as Human Serum Albumin (HAS), Bovine Serum Albumin (BSA) and IgG, in liquid samples. Our numerical modeling is based on our data from the experimental studies of the protein solutions, obtained by microwave dielectrometry setup developed earlier [1].

RESULTS AND DISCUSSION

As a result of our numerical modeling studies, we obtained the optimized structures of the biosensoring structures based on all-dielectric and metal-dielectric metasurfaces, as well as metasurfaces with graphene strips. The unit cells of the developed metasurfaces with optimized structurel parameters are presented in Fig. 1-3.

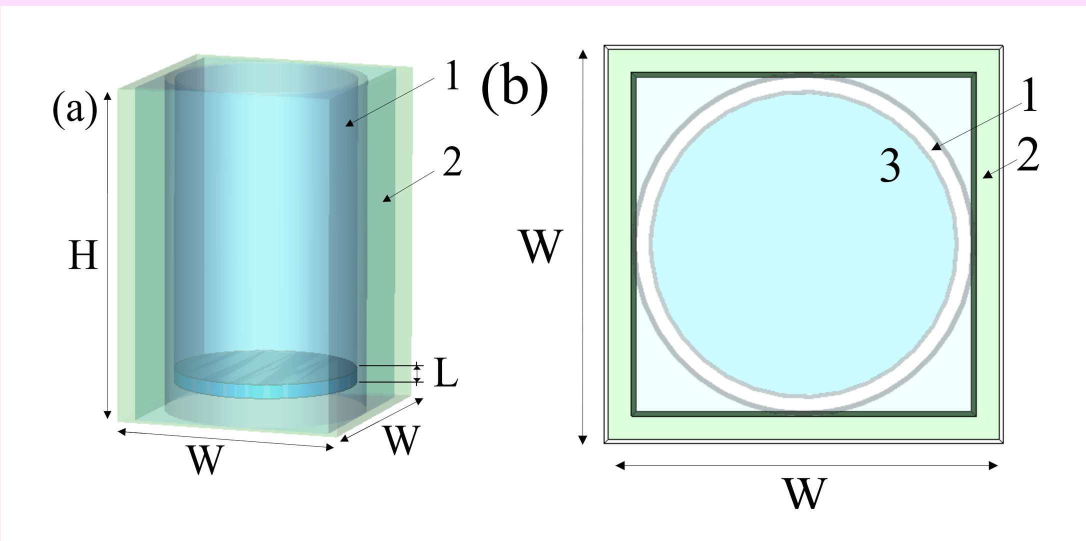

Fig. 1. The unit cell of the multiwell plates (MWP) style metasurface: perspective view (a); top view (b). The numbers correspond: 1 – polycarbonate , 2–- polyamide, 3- the tested liquid layer with thickness L=0.12 mm. W=8.5 mm; H=12mm.

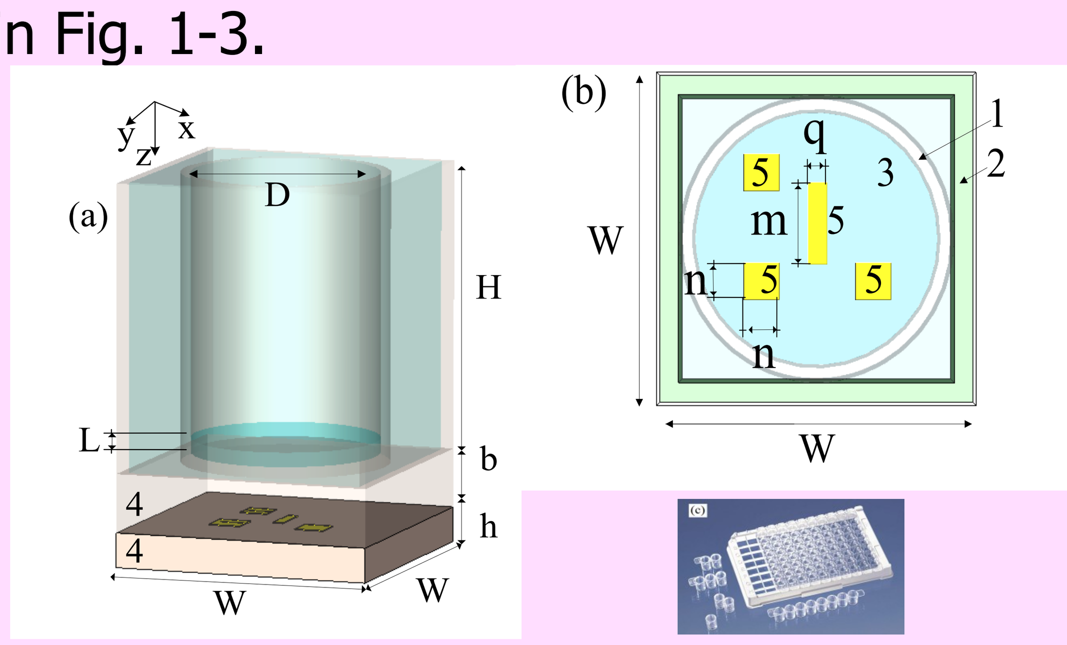

Fig. 2. Metal-dielectric metasurface unit cell structure: perspective view (a); top view (b). Photo of the 96-multiwell laboratory microplate (c). The numbers correspond: 1 – polycarbonate, 2 – polyamide, 3 – the tested liquid, 4 – Teflon , 5 – copper. W=8.5 mm; H=12mm; D=6.75mm; L=0.12 mm; q=0.175mm; m= 0.765mm, n=0.5 mm; b=2.03 mm, h= 1.2mm.

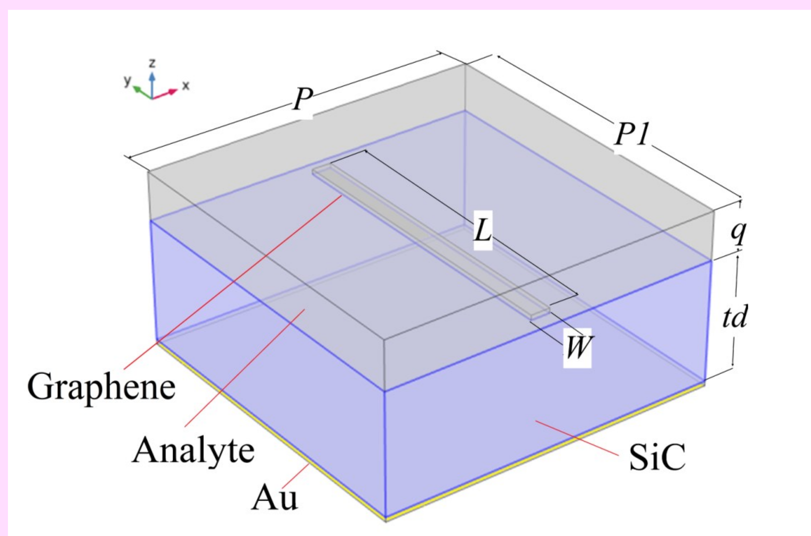

Fig. 3. The unit cell of the graphene-based metasurface, consisting of SiC layer (td = 2.5 μm) with a centrally positioned graphene strip, W = 0.4 μm, L = 6.3μm, P_1 = 2.5 μm and P_2 = 7 μm, tested liquid layer of thickness q=0.5 μm.

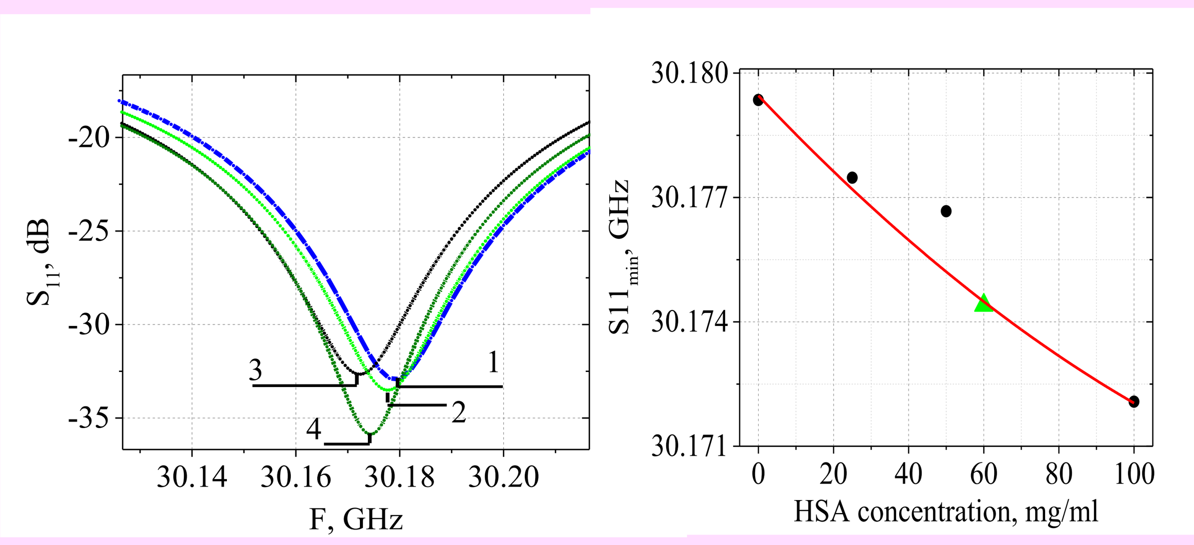

Fig.4. (a) Frequency dependences of the reflection coefficient S_{11} of the MWP metasurface with water (1), tested solutions with 25 mg/ml (2) and 100 mg/ml (3) concentrations of HSA and HSA with trypsin in water solution after 60 min enzymatic reaction time (4); (b) Dependence of the resonance frequency shift of the wave reflection of the MWP metasurface with water and HSA water solution (L=0.12 mm) on the HSA concentration (black points).

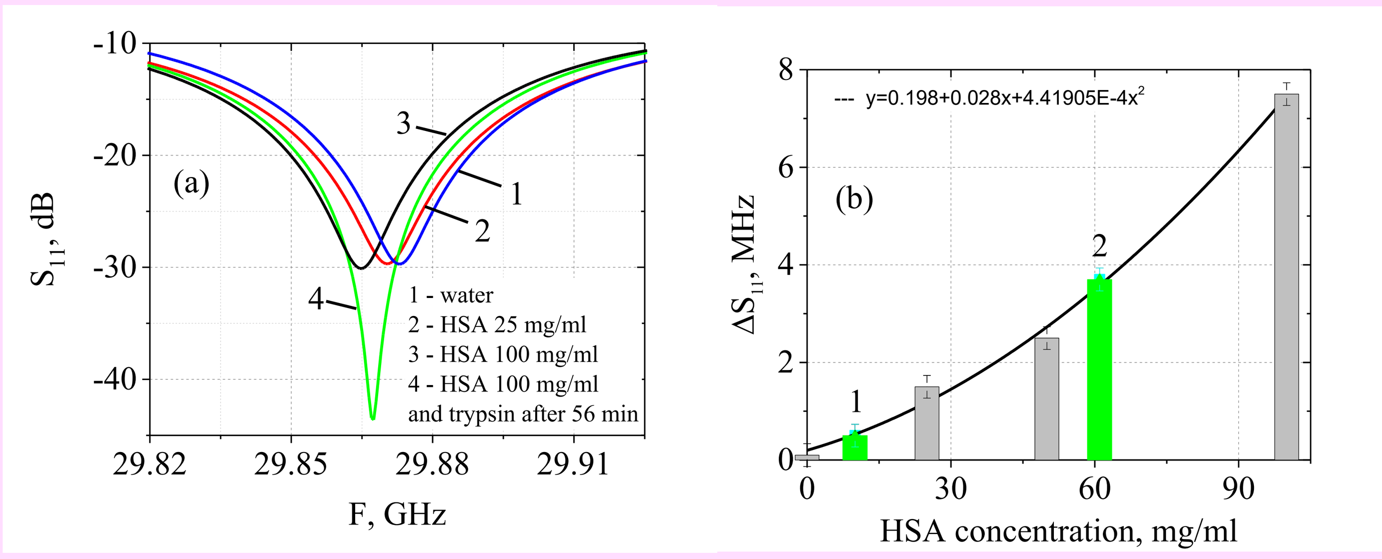

Fig. 5. (a) Dependences of the reflection coefficient S_{11} of the metal-dielectric metasurface with tested liquid: water, protein aqueous solution and protein and trypsin reaction mixture. (b) Dependence of the resonance frequency shift for HSA-water solution (gray columns) and HSA with trypsin reaction mixture after 60 min observation of enzymatic reaction (green columns): 1 – HSA concentration in reaction mixture (for initial concentration of HSA - 25 mg/ml); 2 – HSA concentration in reaction mixture (for initial HAS concentration of 100 mg/ml).

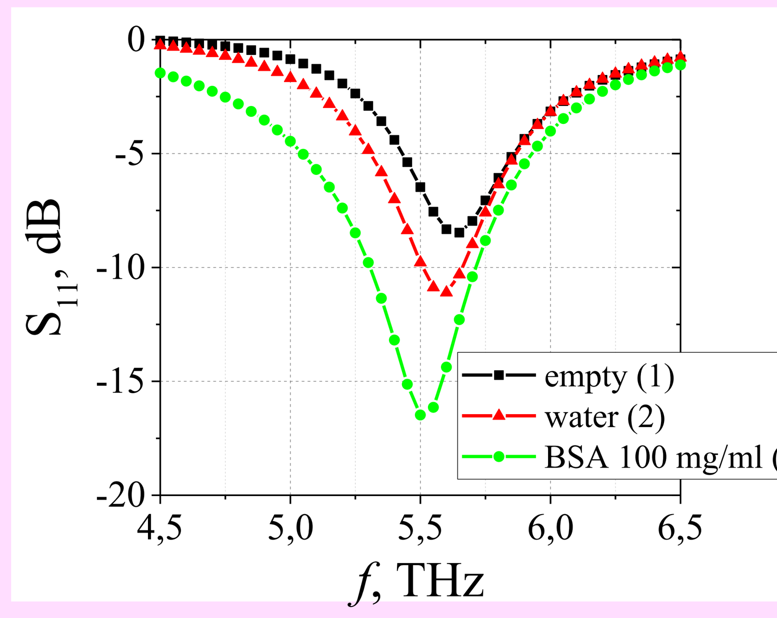

Fig. 6. The reflection coefficient S_{11} of the graphene-based metasurface for different analyte layers: (1) no analyte, (2) water layer, (3) 100 mg/mL BSA aqueous solution.

The sensitivity to the protein concentration determination by using the all-dielectric and metal-dielectric metasurfaces was defined as the change of the resonance frequency shift ΔS_{11} per unit concentration of the analyte in tested liquid ($\Delta S_{11}/\Delta C$). We calculated the sensitivity of the HSA concentration determination in the concentration range from 0 to 100 mg/ml for liquid layer thickness L=0.12 mm and it was equal to 0.073 MHz/(mg·ml^{-1}) for all-dielectric metasurface and to 0.075 MHz/(mg·ml^{-1}) for metal-dielectric metasurface. We can see that the sensitivity values for the all-dielectic and metal-dielectric metasurfaces are similar and are also comparable to sensitivity values available in literature for similar sensors for the proteins and glucose determination. A quantitative evaluation of the performance of the proposed graphene-based sensor was carried out based on the sensitivity $S = \Delta f/\Delta n$ [THz/RIU] to BSA detection, which amounted to 1.6 THz/RIU. The sensitivity of the proposed graphene metasurface sensor for BSA determination is comparable to or higher than that of other reported in the literature THz sensors.

SUMMARY

The developed sensor structures based on all-dielectric, metal-dielectric and graphene microstrips containing metasurfaces demonstrate the reliable sensitivity to the changes of the albumins (HSA or BSA) concentration in the solutions tested. The sensors based on the graphene micro or nanostrips are characterized by the high sensitivity and miniature sizes. We believe that the results obtained from this research can be utilized in the production of the designed biosensors and their subsequent biological testing.

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