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Binary PSO algorithm assisted to investigate the optical sensor based plasmonic nano-bi-domes

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ABSTRACT

In this paper, a coherent perfect absorption (CPA)-type sensor based on plasmonic nano particle is proposed. It consists of a plasmonic nano bi-domes array on top of a quartz substrate. The refractive index changes above the sensor surface, which is due to the appearance of gas or the absorption of biomolecules, can be detected by measuring the resulting spectral shifts of the absorption coefficient. Since the CPA efficiency depends strongly on the number of plasmonic nano-particles and the nano particles location, binary particle swarm optimization (BPSO) algorithm is used to design an optimized array of the plasmonic nano-bi-domes. This optimized structure should be maximizing the absorption coefficient only in the one frequency. BPSO algorithm, a swarm of birds including a matrix with binary entries responsible for controlling nano-bi-domes in the array, shows the presence with symbol of ('1') and the absence with ('0'). The sensor can be used for sensing both gas and low-refractive-index materials in an aqueous environment.

1. Introduction

Nowadays, a large number of commercial gas detecting devices are on the market for a variety of applications. The basic principle is to transform chemical information (e.g. concentration) into an analytically useful signal (e.g.voltage) [1]. There are among others catalytic or metal oxide semiconductor gas sensors based on the resistance change of platinum or a metal oxide after the catalytical reaction of gases. Furthermore, electrochemical sensors based on the principle of galvanic cell or optical gas sensors have been developed.

Optical sensors are widely used for the detection of flammable gases due to their absorption bands in the infrared region (IR sensors). In addition, optical sensors based on the surface plasmon resonance (SPR) effect are known. Today, SPR sensors are commercially used in biochemistry for the detection of liquid analytes [2]. Gas detection was carried out by means of the Surface plasmon resonance (SPR) effect in 1982 [3], but no commercial device has been developed. Surface plasmon resonance (SPR), which based on the excitation of Surface plasmons (SPs), has been widely used in a variety of sensing application, since it is highly sensitive to the environmental refractive index variations [4–6]. The basic principle is: in the sensing medium, a little change in the refractive index due to the appearance of gas or the absorption of biomolecules, will lead to a significant change in wave vector of SPPs, which can be measured by the resulting spectral shifts of the resonant transmission dip. Conventional SPR sensors, which are based on a flat dielectric-metal configuration, have been mainly used

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Fig. 1. Concept of plasmonic sensor by plasmonic nano bi-domes on top of SiO_2 waveguides.

for sensing with visible and near-infrared wavelength. However, for mid- and far-infrared frequencies, the SPRs are weakly confined on the metallic–dielectric interface, which leads to a limited sensitivity [7]. In order to overcome this problem, mid-infrared sensors based on graphene ribbon array are proposed [7,8]. Although most SPR sensors are based on surface plasmons propagating along continuous metal films, in recent years metallic nanoparticles and nanostructures have been increasingly exploited [9]. Metallic nanoparticles have been used in conventional SPR sensors as amplification agents [10] or colloidal aggregation based biosensors [11]. Moreover, localized surface plasmons (LSP) on metallic nanoparticles and nanostructures have been used in LSP-based biosensors [12,13]. The optimization problems in the plasmonic nano-structure area can be divided into two categories. In the first type the continuous optimization algorithm can be performed to engineer the geometrical metal nano-structures [14], whereas in the second type, the binary optimization algorithm can be used to control the presence ('1') or absence ('0') of the metal nano particles in the array [15]. In Ref. [16], binary TLBO algorithm was used and an optical switch based on the dimer plasmonic nano-rods has been proposed. In this work, we design a novel CPA-type SPR sensor based on plasmonic nano bi-domes array for the visible wavelength. The numerical simulations are based on DDA (Discrete-dipole Approximation) method [17]. Since the CPA efficiency depends strongly on the number of plasmonic nano-particles and the nano particles location, BPSO algorithm has been used to control the presence ('1') or the absence ('0') of nano particles in the array and find the best array of plasmonic nano bi-domes from all possible arrays. In BPSO, a group of birds consists a matrix with binary entries; control the presence ('1') or the absence ('0') of nano particles in the array.

2. Background of numerical method

Generally, there are some numerical simulation methods to study the interaction between the light and metal nano particles such as FDTD (Finite-difference Time-domain) [18], FEM (Finite Element Method) [19], DDA (Discrete-dipole Approximation) [17], Mie Theory [20] and Transition matrix (T-matrix) theory [20]. In this paper, DDA is used to study the optical properties of plasmonic nano particles.

3. Principles of plasmonic nano-particle based sensor

The structure of a CPA-type sensor based on plasmonic nano particle is shown in Fig. 1. It consists of a plasmonic nano-particle array on top of a dielectric substrate. n_0 is the refractive indexes of mediums above the nano particles, which changes according to different sensing medium. The material of substrate is quart (SiO2) with refractive index of medium = 1.45 and the material of nano particle is silver. Silver nano-bi-domes have 5 nm diameter and 5 nm edge-to-edge separation gaps. The object is excited by an incident plan wave $E_{inc}(r, t) = E_0 e^{j(kr-wt)}$ where r, t, ω, $k = \omega/c = 2\pi/\lambda$, c, and λ are the position vector, the time, the angular frequency, the wave vector, the speed of light, and the wavelength of incident light, respectively. To calculate the E-field of each dipole time harmonic component -iωt of the E-field is left out. Local field arises from incident light with polar (θ) and azimuth (ϕ) angle at each particle is:

$$E_{inc}(\mathbf{r}_s) = E_0 e^{j\,\mathbf{k}\times\mathbf{r_s}} \tag{1}$$

where

$$k = \frac{2\pi}{\lambda}\hat{k} = \frac{2\pi}{\lambda}[\sin(\theta)\cos(\phi),\ \sin(\theta)\sin(\phi),\ \cos(\theta)] \tag{2}$$

For incident field with P-polarize, the following can be written:

$$\mathbf{E}_0 = [\sin(\theta - \frac{\pi}{2}) \times \cos(\phi),\ \sin(\theta - \frac{\pi}{2}) \times \sin(\phi),\ \cos(\theta - \frac{\pi}{2})] \tag{3}$$

and, for incident field with S-polarize:

$$\mathbf{E}_0 = [\cos(\phi + \frac{\pi}{2}),\ \sin(\phi + \frac{\pi}{2}),\ 0] \tag{4}$$

When the applied field is parallel to one of the principle axes, polarizability, α, is [21]

$$\alpha_s = V\varepsilon_0 \frac{\varepsilon_r - 1}{1 + L_1(\varepsilon_r - 1)} \tag{5}$$