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Sensitive plasmonic-photonic nanosensor as a morphologic mask

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ABSTRACT

In this study, a new nanosensor is assembled in the form of a phantom model to optically scan the breast for early cancer detection based on the plasmonic and plasmonic–photonic interaction phenomena. Sensing is carried out through a user-friendly method by improving imaging through the traditional optical tomography method. The novelty of the designed sensor is attributed to the coupling of the nanoparticle plasmonic near-field intensity to the far-field region (photonic mode interaction with the near-field plasmon resonance). It is shown that the plasmonic–photonic interaction has a dramatic influence on the gradient image and therefore, the edge detection and segmentation of the image are effectively altered. This is due to the fact that the plasmonic fields of the nanoparticles in the near- and far-field manipulate the field gradient, which leads to a modification of the intensity discontinuities at different interfaces. In fact, it is well-known that the fundamental idea behind edge detection is utilized to detect parts of the image where the intensity varies rapidly. Based on this knowledge, interestingly, it is shown that the segmentation and edge detection of the image are improved by the manipulating optical properties of the mask.

1. Introduction

Unfortunately, it is reported that cancer is the second leading cause of death in the world; most medical institutes attempted to find safe treatments for its early and easy detection. Recently, the development of nano-medicine is considered to be among the most promising advances in cancer treatment, referring to the application of small agents known as “functionalized nanoparticles (NPs)” to sense and detect in high-resolution imaging, and also to be used as therapy agents [1–4]. When this novel method was compared with other available common therapies, such as chemotherapy, radiotherapy, and surgery [5–7], published reports have confirmed that nano-medicine has several crucial advantages, including accurate targeting, localized drug delivery, and high-resolution imaging. For instance, drug delivery in nano-medicine, which is its most important attribute, shows higher accuracy, compared to the traditional methods for cancer treatment; and moreover, it could be regulated with high-precision targeting and imaging. It is well-known that the main disadvantages of the common methods, such as chemotherapy, are attributed to the use of non-targeted drugs for destroying cancerous tumors. In the nano-medicine fields, accurate detection of tumors or cancer cells was carried out by an effective method, such as active targeting. In this method, the main agents, such as NPs, are functionalized with several important biological factors or linkers, owing to bio-compatibility and other aspects. One of the most important features of active targeting is to attach the biological agents to the NP surfaces in order to produce a multi-functional sensor, using which simultaneous tasks could be performed [1–3], [8–11]. Investigations have shown that nano-medicine techniques have enormous advantages, but they are not regarded as user-friendly methods; in fact, they must be used in clinics. Thus, at present, the main research objectives in this regard are to find a user-friendly method. In this article, we study a user-friendly method, by which optical scanning (especially for breast cancer in the improved version) can be performed without the need for any active targeting agents or clinical equipment. Thus, the interactions of light with different media are analyzed; and the scattered photons are detected by a sensitive sensor. It was reported that the light absorption in a real tissue is very high and the detected photons by the nanosensor are negligible [12,13]; herein, to overcome this critical problem, we used different wavelengths, such as 532, 650, 780, and 808 nm, based on the absorption rates in the tissue materials, such as H_2O, oxy- and deoxy-hemoglobin. Moreover, a highly sensitive detector must be

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designed to detect a small number of scattered photons. This means that images should be created with a small number of scattered photons by a high-sensitivity nanosensor. The most important case in this study is using gradient image improvement by the nanosensor as a virtual morphological mask before image processing. In fact, the gradient image is implicitly manipulated by the plasmonic effect of the NPs based on field non-uniformity, which causes the variation in image gradient. This non-uniformity due to the plasmonic and plasmon–photonic interaction of NPs has an effective influence on image segmentation and edge detection; this contributes to the edge detection principle of finding parts of the image where the intensity varies rapidly. These factors are the most important cases in image processing, by which critical objects, such as tumors could be clearly detected. It was reported that a pure image processing was performed in CT [14], MRI [15,16], and PET images [17] by these factors. In the referenced methods, image processing is an indispensable factor, while the new approach used in this work can improve the captured images. In this study, we consider a new method to enhance the image segmentation of a phantom model; in addition, the designed image processing toolbox can be applied to the image of the traditional system. Moreover, we used different effective media (TiO_2/Au, SiO_2/Au, Agar/Au, and Si_3N_4/Au) to analyze the scattered photons [18,19]. In fact, the effective complex refractive index of the nanosensor medium and photon absorption by the detector surface could be manipulated using engineering techniques. This contributes to the manipulation of the nanosensor medium plasmonic features, such as the localized plasmonic effect and its coupling to the far-field by photonic engineering [20,21]. By the use of the plasmonic effect of the NPs on the detected photons, any abnormalities in the medium, owing to their different optical properties, are recognized. Subsequently, it is clearly analyzed with edge detection and image segmentation by using the improved gradient image [24]. Finally, the scattered photons from the nanosensor are detected by a sensitive charge-coupled device (CCD), and after image processing, the finalized image is sent to a mobile phone for use on a user-friendly device. In the following section, the mathematical and theoretical background of this work is presented.

2. Theoretical and background

2.1. The NPs plasmonic near-field coupling to far-field region

In this section, the theoretical background is presented. For this reason, we start with Fig. 1, which schematically illustrates the interaction of an electromagnetic wave with NPs and a medium, as well as the detection of the scattered light by a detector. For simplicity, the incidence of a plane wave was supposed and based on this assumption; the incidence field is given by:

$$E_{inc}(r,t) = E_0 \cdot e_r \exp(i(kr - \omega t)) \tag{1}$$

where E_0, e_r, k, ω, and r are the field amplitude, polarization, wave number, angular frequency, and position vector, respectively. By incidence of the plane wave on the NPs, based on Fig. 1, two different types of fields, including near-field around the NPs and far-field, which is far away from the NPs, are generated. The far-field is a very important case in this study; therefore, it will be investigated in some detail. In addition, the NPs' plasmonic field coupling to the far-field region or plasmonic–photonic interaction will be considered as an original factor in the nanosensor design. By interaction of the incident wave with the NPs, they start to resonate and, perhaps, the plasmonic resonance can occur. Therefore, the NPs' plasmonic resonance effects are calculated at typical desired points inside the medium based on the NPs' polarizability. By considering the medium as $n \times m$ separate points (focal points), we introduce the scattering electric field [22] for each focal point as follows:

$$E_{sct(m,n)} = \sum_{j=1}^{Np} \left(\frac{\exp(ikr_{mn})}{r_{mn}}\right) \cdot \left\{ k^2 \left(r_{h_{mn}} r_{h_{mn}} - I_3\right) + \left(\frac{ikr_{mn} - 1}{r_{mn}^2}\right) \times \left(3 r_{h_{mn}} r_{h_{mn}} - I_3\right) \right\} \cdot P_j \tag{2}$$

where N_p, r_{mn}, r_{hmn}, I_3, and P_j are the number of NPs, radial coordinate of the position vector, position unit vector, matrix identity, and NPs' polarization, respectively. Moreover, P_j is given by:

$$P_j = \alpha_j \cdot E_j, E_j = E_{inc,j} + E_{sca,j}. \tag{3}$$

In Eq. (3), α_j, $E_{inc,j}$, and $E_{sca,j}$ are the polarizability, incidence field, and NPs' scattering field, respectively. For all focal points, we defined the scattering field's matrix as in Eq. (4). In this equation, $E_{sct}(m, n)$ and $E_{sct}(j_i, i = 1 \ldots 4)$, represent the scattering field in the medium containing normal and abnormal optical properties, respectively, and this matrix is nominated as the scattering far-field matrix. Actually, the scattering far-field matrix came from the far-field radiation of NPs and is due to the NPs' plasmonic coupling to the far-field region. For instance, by changing the inter-NP distance, this matrix element will be altered. After calculating the scattering far-fields at any points, $j = (m, n)$, of the medium, each point on the detector senses the destructive or instructive effects of the focal points. This means that by engineering the detector effective material complex refractive index, the focal points effect can be managed. Consequently, by regarding Eq. (4), the medium is divided into $N \times M$ elements at time t; therefore, this matrix, the elements of which are the initial value of the virtual mask, is generated for time evolution and finally, it will be concluded to produce an image on the CCD. It is notable that some points in the matrix arrays contribute to the different medium at which the incident light interacts with different optical properties, rather than the normal medium; therefore, the scattering fields show different properties.

$$E_{sct}(r,t) = \begin{bmatrix} E_{sct(1,1)} & E_{sct(1,2)} & E_{sct(1,3)} & \cdot & \cdot & \cdot & E_{sct(1,N-2)} & E_{sct(1,N-1)} & E_{sct\ (1,N)} \\ E_{sct(2,1)} & \cdot & & & & & & & \cdot \\ E_{sct(3,1)} & & \cdot & & & & & & \cdot \\ \cdot & & & \cdot & & & & & \cdot \\ \cdot & & & & E_{sct(j_1)} & E_{sct(j_2)} & \cdot \ \cdot & \cdot & \\ \cdot & & & & E_{sct(j_3)} & E_{sct(j_4)} & \cdot \ \cdot & \cdot & \\ & & & & & & \cdot \ \cdot & & \\ E_{sct(M-2,1)} & & & & & & & & E_{sct(M-2,N)} \\ E_{sct(M-1,1)} & & & & & & & & E_{sct(M-1,N)} \\ E_{sct(M,1)} & & & & & & E_{sct(M,N-2)} & E_{sct(M,N-1)} & E_{sct(M,N)} \end{bmatrix} \tag{4}$$