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Design of terahertz metal-dielectric-metal waveguide with microfluidic sensing stub

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ABSTRACT

We design a terahertz (THz) metal-dielectric-metal (MDM) waveguide sensor with embedded microfluidic channel suitable for sensing the refractive index variations in liquid. The transmission properties are described using transmission line model (TLM) and numerically simulated using finite-difference time domain (FDTD) method. The sensing characteristics of the structure are systematically analyzed through the examination of the transmission spectrum. The results reveal a series of pronounced resonance peaks in the transmission spectrum, which has linear relationship with the refractive index variation of the material under investigation. For detecting the presence of various cancer cells flowing through the microfluidic channel, we designed and optimized the structural parameters of the THz-MDM sensor and achieved a theoretical value of the refractive index detection sensitivity as high as 0.457 THz/RIU for a 20 μm × 24 μmcross-section channel. This work shows great promise toward realizing a compact THz refractive index sensor with high sensitivity for identifying the signatures of biological samples in liquid.

1. Introduction

Terahertz spectroscopy, which covers radiation band ranging 100 GHz to 10 THz, has intrigued tremendous interests in the biological, chemical sciences as well as clinical research communities. Studies have shown that terahertz waves could identify intermolecular and intramolecular hydrogen bonds in biological materials such as amino acids [1], polypeptides [2], DNA [3], protein [4], sugars [5], pharmaceuticals [6]. Applications such as pathological examinations of tissues [7] and identification of drugs or explosives in postal packages can also be realized with this real-time, marker-free and non-ionizing technique [8,9].

However, there are a few limitations for applying THz spectroscopy in biological detection in water solutions. Firstly, water has huge absorption of THz waves due to the excitation of both water dipolar moments and the hydrogen bond network. The method of using attenuated total reflection can partially solve the problem, but it will encounter the large signal loss from the in and out of the coupling prism [10]. Second, relatively larger volume of bio-samples would be needed for THz analyses based on transmission, since the wavelength of 1 THz is about 300 μm and the wrist of the correspondent Gaussian beam is therefore above 1 mm. Large quantities of samples to be studied may be hard to collect in reality. To overcome such difficulties in sample volume, microfluidic systems have been proposed for accurate volume control of the solutions to perform THz spectroscopy [11–14].

Alternatively, to address the above limitations, different THz wave manipulation structures such as parallel plate waveguides (PPWGs) or similarly metal-dielectric-metal (MDM) waveguides were proposed, since they can support modes with deep sub-wavelength scale and high group velocity over a very wide range of frequencies extending from DC to visible scale. This is due to the formation of the dispersion-less transverse electro-magnetic (TEM) mode or the similarly MDM fundamental mode (TM0) considering surface plasmon polaritons(SPP) [15]. In THz domain, the highly localized field inside the PPWGs has been used to increase the sensitivity of a measurement [16–18]. Furthermore the stub like resonator has been integrated in the THz PPWG as a refractive index sensor for liquids in a microfluidic platform [19,20], but they did not use the TM0 mode and the influence of THz SPP at metal-dielectric interfaces had not been explored though the metals behave almost like a perfect conductor (PEC).

In this paper, we proposed a compact (several tens of micrometers width and several hundreds of micrometers length) and highly sensitive liquid refractive index sensor based on a two layers

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THz MDM stub structure. To make optimized designs, we not only employed the numerical technique such as the finite difference-time domain method (FDTD), but also generated the transmission line model (TLM) for the proposed sensing structure. TLM is a fast and reliable analytical approach investigated for optical bands [21–24], but few applications are reported in the THz band. The characterization of the impedance of the MDM by TLM can be useful for a better understanding of the MDM based THz components. TLM analytical modal also provides a design tool to generate complex plasmonic structures since the amount of calculation will dramatically drop when the optimization is necessary compared with EM popular full wave numerical methods such as FDTD and FEM. The model allows us to rapidly and precisely simulate the transmission spectra of THz MDM stub sensor considering SPP. The sensing characteristics of the proposed THz MDM stub structure were analyzed in detail. The result show that THz MDM stub integrated with a microfluidic channel can be a very promising for both molecular and cellular analyses towards point-of-care type of biological sensing.

2. Structure and method

The proposed THz MDM wave guide with a two layers stub structure is schematically shown in Fig. 1(a) and (b), in which the stub includes a solid spacing dielectric layer and a liquid biomaterial sample layer. Consider the possible applied scenario in Fig. 1 (a) where the thickness t of the structure is thick enough to simplify the sensor into a 2D scheme in Fig. 1(b). The channel (ε_{air}) width is d. The two layers stub with width w includes a dielectric spacing layer (ε_d) with height h_1 and a biomaterial sample layer (ε_s) with height h_2. When the biomaterial sample is liquid flowing in tens of microns microfluidic channel, the solid dielectric spacing layer is necessary in an integrated system.

It has been revealed that the transmission of an MDM waveguide can be described using the analogy between single-mode MDM waveguides and microwave transmission lines [21–24]. Then, the waveguide of width d is replaced by a transmission line of characteristic impedance

$$Z(d) = \frac{\beta(d) d\eta}{k_0 \varepsilon} \tag{1}$$

where $\beta(d)$ is the SPP propagation constant at wavelength λ, ε_d is the relative permittivity of the dielectric in the MDM, η is the wave impedance in the dielectric, and $k_0=2\pi/\lambda$. The analogy will be effective under the quasi-static approximation with $d \ll \lambda$ in which only single fundamental mode (TM0) can be supported. The $\beta(d)$ can be calculated by the dispersion relationship for the TM-SPP or a simplified approximation [25]

$$\beta(d)=k_0\sqrt{\varepsilon_d - 2\varepsilon_d\frac{\sqrt{\varepsilon_d - \varepsilon_m}}{k_0 d \varepsilon_m}} \tag{2}$$

where ε_d and ε_m are the relatively permittivity of dielectric and metal respectively. When $|\varepsilon_m| \to \infty$**?** the $\beta(d)=k_0 n_{eff,d} \cong k_0 n_d$, where $n_{eff,d}$ is the effective index of the MDM with the dielectric of the refractive index n_d.

In Fig. 1(b) the characteristic impedance of the wave guide of air Z_{air} can be obtained from Eq. (1) by substituting vacuum for dielectric. At the same time the stub sections of the waveguide on the spacing dielectric and the sample can be represented by two finite-length transmission lines of characteristic impedance Z_d and Z_s with the corresponding relatively permittivity ε_d and ε_s, and replacing d by w.

The whole THz MDM wave guide with two layers stub consists of the three transmission line segments, which need to be connected in parallel in Fig. 1(c). The equivalent network presentation shown in Fig. 1(d) . The part of transmission corresponding to the two layers stub can be replaced by effective impedance

$$Z_{stub} = Z_d \frac{Z_L' + jZ_d \tan(\beta_d h_1)}{Z_d + jZ_L' \tan(\beta_d h_1)} \tag{3}$$

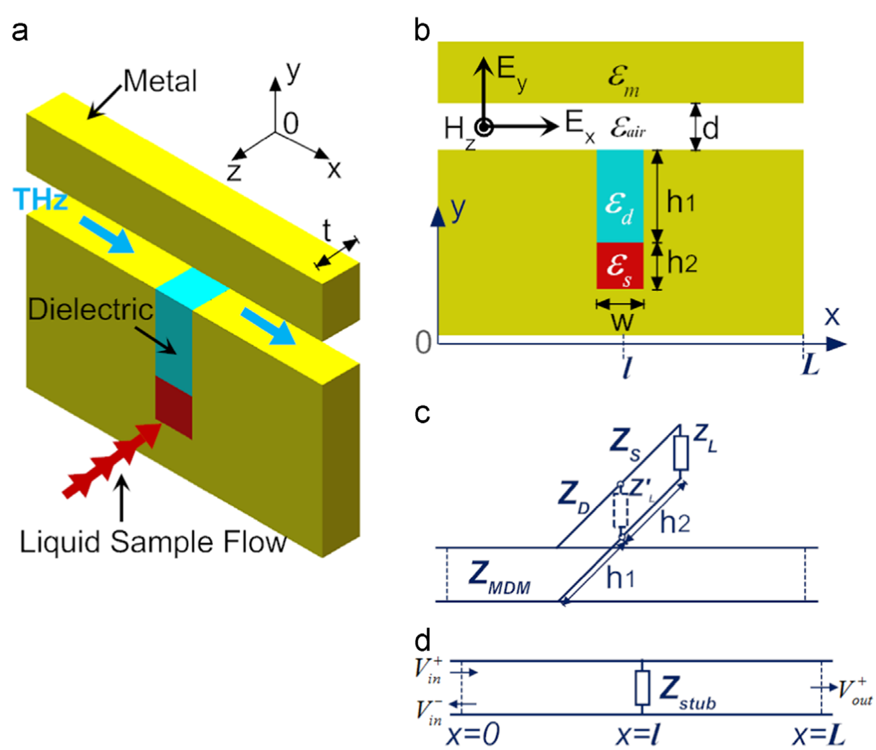

Fig. 1. Design of a THz MDM waveguide with a two layers stub including a dielectric spacing layer and fluidic layer with samples under investigation. (a) 3-D Schematic; (b) 2-D Schematic; (c) the equivalent transmission-line representation, and (d) its simplified circuit model.