Advanced Optical Terahertz Fingerprint Sensor Based on Coherent Perfect Absorption

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1. TE mode calculation

In terms of TE mode, the permittivity is described by the Drude model [1].

$$\varepsilon_{(TE)} = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + j v_c \omega} \tag{1}$$

Where $\varepsilon_\infty = 15.68$ is the high-frequency limit permittivity and ω denotes the angle frequency, v_c is the carrier collision frequency, taken as 0.1π THz, ω_p is plasma frequency, the function of which is expressed as $(Ne^2/\varepsilon_0 m^*)^{1/2}$, e, ε_0 and m^* are the electron charge, the permittivity in the vacuum and the effective mass of the carrier.

The concentration of the free carriers in the InSb layer is given by the empirical formula below [2][3]:

$$N(m^{-3}) = 5.76\times10^{14} T_0^{1.5} \exp\left[-0.26/(2\times8.625\times10^{-5}\times T_0)\right] \tag{2}$$

The calculation method is the same as in TM mode.

Supposing that the relative permeability is 1, then, the effective refractive index for the TE wave is expressed as [1]:

$$n_{(TE)} = \sqrt{\varepsilon_{(TE)}} \tag{3}$$

Hence, the transfer matrices of the InSb layers for the TE waves can be expressed as [1]:

$$M_{(TE)} = \begin{pmatrix} \cos(k_{(TEz)}d) & -\frac{j}{\eta_{(TE)}}\sin(k_{(TEz)}d) \\ -j\eta_{(TE)}\sin(k_{(TEz)}d) & \cos(k_{(TEz)}d) \end{pmatrix} \tag{4}$$

where $\eta_{(TE)} = \sqrt{\varepsilon 0 / \mu 0} n_{(TE)} \cos(\theta)$, $k_{z(TE)} = n_{(TE)} \cos\theta \cdot \omega / c$ refers to the component of the incident waves in the z-direction.

As for the other dielectric, they have the same calculation in TM mode and TE mode.

Reference

[1] You-Ming, Liu, et al. "Nonreciprocal wide-angle bidirectional absorber based on one-dimensional magnetized gyromagnetic photonic crystals." Chinese Physics B 32.4 (2023): 44203-044203.

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2. Simulation and calculation method

2.1 Transfer matrix method

As stated in the paper, our proposed sensing structure has the following dielectric layer： Air, Silicon, Teflon, InSb, and the sample (α-lactose), where Air, Silicon, and Teflon belong to the common dielectrics, InSb is a spin medium, Air, Silicon, Teflon, and α-lactose belong to the conventional dielectric layers. If there is no load sample, the cavity is filled with air.

According to the Drude-Lorentz model, the permittivity of α-lactose can be obtained as follows [1][2].

$$\varepsilon_r = \varepsilon_{\infty 2} + \sum_{p=1}^{\infty} \frac{\Delta\varepsilon_p \omega_{p2}^2}{\omega_{p2}^2 - \omega^2 - j\gamma_p \omega} \tag{5}$$

For simplification, only the first-order absorption resonance of α-lactose is taken into account. Hence, the function can be expressed as:

$$\varepsilon_r = \varepsilon_{\infty 2} + \frac{\Delta\varepsilon_p \omega_{p2}^2}{\omega_{p2}^2 - \omega^2 - j\gamma_p \omega} \tag{6}$$

The paper shows the values of all the physical quantities required in order to calculate them.

In the calculation, due to normalization, the refractive index of α-lactose can be calculated by the following equation:

$$n_{(\alpha-lactose)} = \sqrt{\varepsilon_r} \tag{7}$$

As for conventional dielectric layers, the transfer matrix is:

where $\delta_i = -2\pi \cdot n_i \cdot d_i \cdot \cos\theta_i / \lambda$ and $\eta_i = (\varepsilon_0/\mu_0)^{1/2} \cdot n_i \cdot \cos\theta_i$.

It is worth noting that the thickness of the cavity varies with the thickness of the sample:

$$d_{cavity} = \frac{1}{2}(268\mu m - d_{Teflon} - d_{\alpha-lactose}) \tag{8}$$

All the values of all physical quantities required are given in the paper.

As for magnetized InSb layers, We first need to calculate the value of the concentration of the free carriers in InSb from the temperature according to the formula below [3][4]:

$$N(m^{-3}) = 5.76\times10^{14} T_0^{1.5} \exp\left[-0.26/(2\times8.625\times10^{-5}\times T_0)\right] \tag{9}$$

Hereby we assume an operating temperature of 303K.

We calculate the plasma frequency by bringing the calculated N into the following equation [5]:

$$\omega_{p1} = \sqrt{\frac{e^2 N}{\varepsilon_0 m^*}} \tag{10}$$

Due to the effect of the applied magnetic field, we can obtain the cyclotron frequency according to the following equation:

$$\omega_c = \frac{eB}{m^*} \tag{11}$$

Here the magnetic field strength is determined as 1.23T.

Thus, we can calculate each component of the tensor according to Eqs.(6) and (7) [3].

$$\varepsilon_{InSb} = \begin{pmatrix} \varepsilon_x & 0 & \varepsilon_{xz} \\ 0 & \varepsilon_y & 0 \\ -\varepsilon_{xz} & 0 & \varepsilon_x \end{pmatrix} \tag{12}$$

where

$$\varepsilon_x = \varepsilon_{\infty1} - \varepsilon_{\infty1}\frac{\omega_{p1}^2(\omega + j\nu_c)}{\omega\left[(\omega + j\nu_c)^2 - \omega_c^2\right]} \tag{13}$$

$$\varepsilon_y = \varepsilon_{\infty1} - \varepsilon_{\infty1}\frac{\omega_p^2}{\omega(\omega + j\nu_c)} \tag{14}$$

$$\varepsilon_{xz} = \varepsilon_{\infty1}\frac{j\omega_{p1}^2\omega_c}{\omega\left[(\omega + j\nu_c)^2 - \omega_c^2\right]} \tag{15}$$

In the programmed solution, we calculate the effective refractive index under TM polarization [6]:

$$n_{TM} = \sqrt{\frac{\varepsilon_x^2 - \varepsilon_{xz}^2}{\varepsilon_x^2}} \tag{16}$$

The above results are brought into the following equation to calculate the transmission matrix [7]:

$$M_{InSb} = \begin{pmatrix} \cos(k_z d) + \sin(k_z d)\cdot\frac{k_x\varepsilon_{xz}}{k_z\varepsilon_x} & -\frac{j}{\eta}\left[1 + \left(\frac{k_x\varepsilon_{xz}}{k_z\varepsilon_x}\right)^2\right]\cdot\sin(k_z d) \\ -j\eta\sin(k_z d) & \cos(k_z d) - \sin(k_z d)\cdot\frac{k_x\varepsilon_{xz}}{k_z\varepsilon_x} \end{pmatrix} \tag{17}$$

All parameters can be found and calculated in the paper.

Subsequently, we cumulatively multiply the transmission matrix of each media layer according to the arrangement of the structure.

$$M = M_{Si}M_{Air}M_{Si}M_{Air}M_{Si}M_{Air}M_{Si}M_{InSb}M_{cavity}M_{\alpha-lactose}$$
$$M_{Teflon}M_{Cavity}M_{InSb}M_{Si}M_{Air}M_{Si}M_{Air}M_{Si}M_{Air}M_{Si} \tag{18}$$

Next, we can derive the reflection coefficient *R*c and the transmission coefficient T_c according to the four elements of the matrix ***M*** [8].

$$R_c = |r|^2, \tag{19}$$

$$T_c = |t|^2, \tag{20}$$

where

$$r = \frac{(m_{12}\eta_{N+1} + m_{11})\eta_0 - (m_{22}\eta_{N+1} + m_{21})}{m_{11}\eta_0 + m_{21}m_{12}\eta_0 + \eta_{N+1} + m_{22}\eta_{N+1}}, \tag{21}$$

$$t = \frac{2\eta_0}{m_{11}\eta_0 + m_{21} + m_{22}\eta_{N+1} + m_{12}\eta_0\eta_{N+1}}, \tag{22}$$

Coherent absorption coefficient we can derive to the following equation to calculate [9]:

$$A_c = 1 - (|t| - |r|)^2 - 2|t||r|\left(1 + \frac{2|I_+||I_-|\cos\Delta\varphi_1\cos\Delta\varphi_2}{|I_+|^2 + |I_-|^2}\right) \tag{23}$$

To realize coherent perfect absorption, the initial phase difference between the two incident waves is determined as 0 degrees, and the two incident waves are equal.

The specific calculation flow chart is shown in Fig.1.

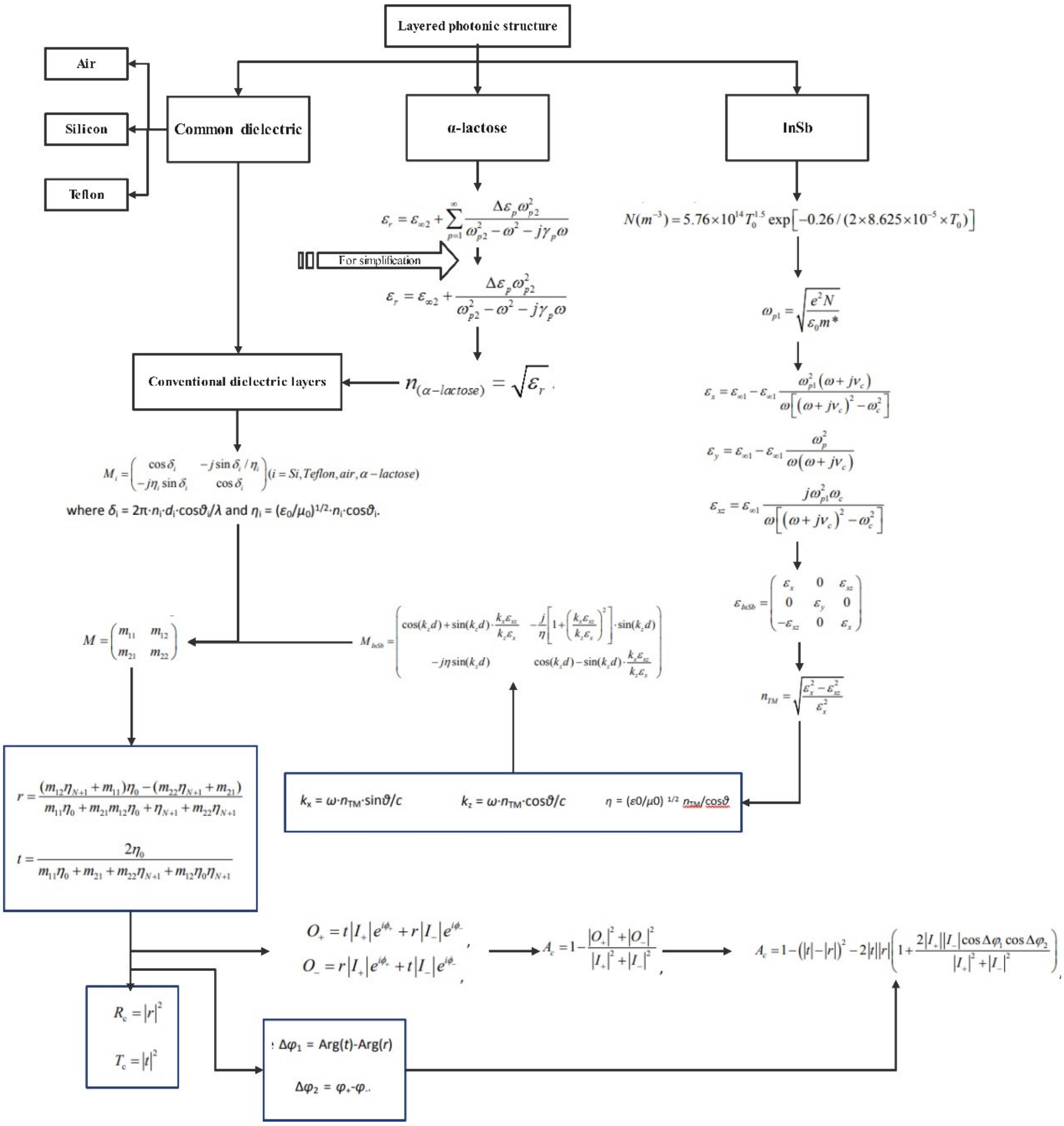

Fig.1 The specific calculation flow chart

2.2 Amplitude modulation

First, we define the relative amplitude A, which is the ratio of the two incident wave amplitudes. It can be assumed that A<1.

$$A = \frac{|I_-|}{|I_+|} \tag{24}$$

Herein, we use amplitude modulation, which regulates and compensates for absorption via changing the relative amplitude A. As shown in Fig.2, the flow chart of this terahertz fingerprint sensing scheme is illustrated.

We compensate and regulate the variation of coherent absorption caused by different thicknesses of the sample by regulating the relative amplitude of the incident wave, and the coherent absorption coefficient is maintained at 0.5.

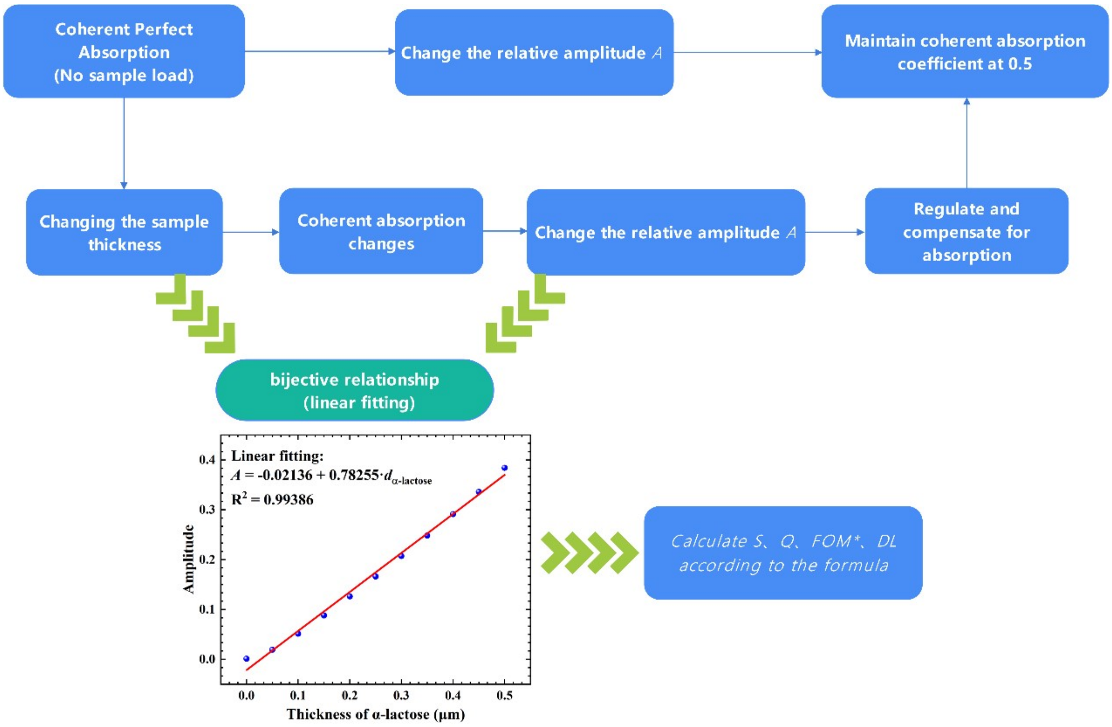

Fig.2 The flow chart of this terahertz fingerprint sensing scheme

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[2] Z. Han, A. M. Soehartono, B. Gu, X.Wei, K. T Yong and Y. Shi, "Tunable hybridization induced transparency for efficient terahertz sensing." Optics Express 27.6 (2019): 9032-9039.

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[4] J. Sui, D. Zhang, and Zhang, H. "Logical OR operation and magnetic field sensing based on layered topology." Journal of Physics D: Applied Physics 55.41 (2022): 415001.

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[8] R. Ning, S. Liu, H. Zhang, B. Bian, and X. Kong. "A wide-angle broadband absorber in graphene-based hyperbolic 16 metamaterials." The European Physical Journal-Applied Physics 68.2 (2014).

[9] W. Zhu, F. Xiao, M. Kang, and M. Premaratne. "Coherent perfect absorption in an all-dielectric metasurface." Applied Physics Letters 108.12 (2016): 121901.

3. Fabrication method

The analyte place is left empty in the experiment design so that the measurement object can be inserted in its place. All other media, excluding the analyte, are filled to their corresponding positions.

The etching method can be utilized to create one-dimensional layered photonic crystals. The required number of layers and the thicknesses of the corresponding layers can be etched on the Si substrate, and then the materials involved in the structure can be filled [1].

To actualize the structure, we use the etching procedure during the production process. The silicon wafer is chosen as the substrate, and then the wet anisotropic etching technique is used to etch vertical grooves of varied thicknesses based on the corresponding scale of the materials in the proposed structure in the silicon wafer. The wet anisotropic etching technique involves the use of a 44wt% potassium hydroxide (KOH) aqueous solution at 85ºC, while the thermally grown SiO2 layer serves as the hard mask for the etching process. By following the prescribed conditions of our theoretical research on the silicon substrate, grooves can be produced, and the appropriate materials can be inserted in the corresponding positions. The ideal structure is achieved when the substrate's height and width can be freely extended, resulting in features that align with our theoretical analysis [2]. The detailed manufacturing process flow of our suggested structure is shown in Figs.3(a)-(f).

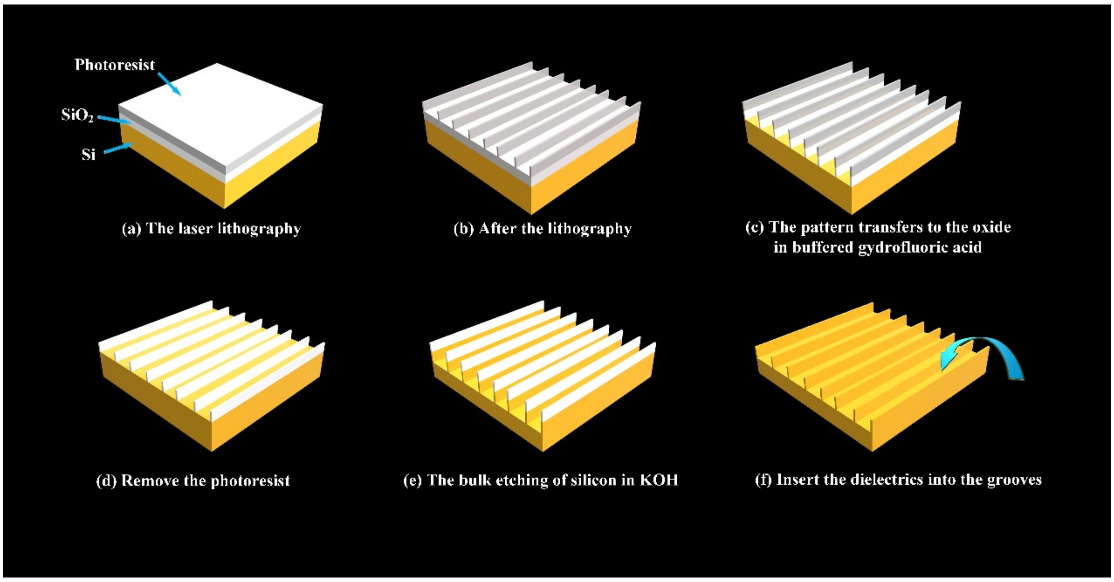

Fig.3 The diagram of the fabrication process flow of the proposed structure.

Reference

[1] Renilkumar M and Nair P 2011 *Optical Materials* **33** 853

[2] Tolmachev V A, Granitsyna L S, Vlasova E N, Volchek B Z, Nashchekin A V, Remenyuk A D 2002 *Semiconductors* **36** 932