Indium Antimonide (InSb) Waveguide based THz sensor

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***Abstract*- We demonstrate the sensing capability of InSb based planar THz waveguide with stubs, which can sense biomolecules of a few micro liter quantity in de-ionized (DI) water. We chose Bovine Serum Albumin (BSA), a well-known standard protein molecule to investigate the sensing property. The calculated absorption coefficient from the Fourier transformed transmission characteristics show prominent changes with different concentrations of BSA, demonstrating the potential application of the device to function as a simple THz sensor.**

I. INTRODUCTION

THz science is gaining its potential in the field of sensing and imaging. Some of the molecules have their vibrational or rotational energy transitions in the THz frequency range, which put us to explore, identify and classify them. THz sensing has attracted considerable attention in the field of biochemistry and medicine. THz waveguides, loaded with such materials, have shown capability to detect materials with high sensitivity [1]. A parallel plate waveguide with a resonant cavity, forming a part of a lab-on-chip device, was demonstrated to function as a highly sensitive refractive index sensor with a sensitivity of 91.25 GHz/RIU [2]. A THz metamaterial device, consisting of symmetric split ring resonators, was exploited as ultrasensitive refractive index sensor, possessing a sensitivity of 36.7 GHz/RIU and 23.9 GHz/RIU when Fano and Quadrupole resonances, respectively, were excited [3]. THz antenna [4] was used to detect bacterial layers with high sensitivity.

The objective of this paper is to investigate the sensing capability of a Semiconductor–Insulator–Semiconductor (SIS) THz InSb based plasmonic waveguide with stubs along the waveguide acting as sensing elements. We experimentally demonstrated the transmission characteristics of the InSb waveguide [5] using THz time-domain spectroscopy (THz-TDS). The BSA is a standard protein molecule [6]. We measured the THz absorption coefficient for two different concentrations of BSA dissolved in DI water (BSA-W) loaded in our device; vary significantly over the frequency range 0.2 – 1.0 THz.

II. THz InSb WAVEGUIDE

THz waveguide devices were fabricated on InSb pellet using conventional laser micromachining. A schematic of the device is shown in Fig. 1(a). It has slots with vertical height D, forming a waveguide of width G and length A and with stub of length L along the waveguide of stub-widths W. InSb is a III-V semiconductor with a band gap of 0.17 eV at 300K and large electron mobility. In THz frequency range, permittivity of InSb calculated using Drude free electron model is similar to that of metals. This makes the InSb a good candidate for THz Plasmonic devices [7].

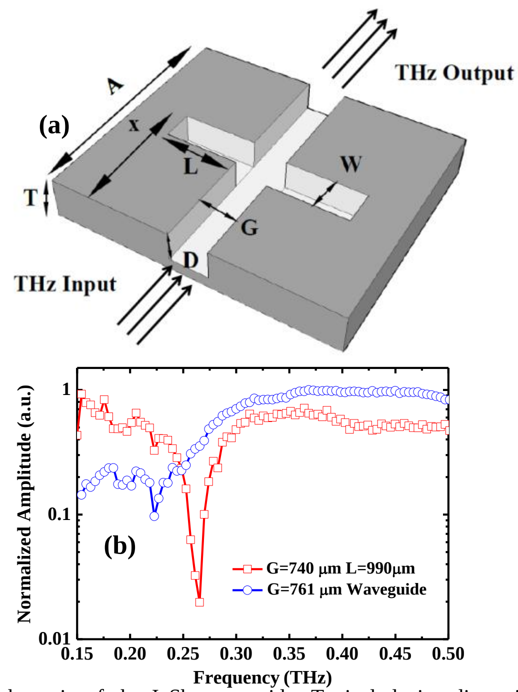

Fig.1(a) Schematic of the InSb waveguide. Typical device dimensions: Stub length (L) =1000µm, Stub width (W) = 750µm, Width of the waveguide (G) = 750µm, Vertical height of the waveguide (D) = 1.8mm, Thickness of the slab (T) = 2mm, Position of the stub (x) = 6mm, Length of the waveguide (A) = 12mm. **(b)** Measured transmission spectra of the THz pulse for InSb waveguide with stub of G = 740µm and L = 990µm, and InSb waveguide without stub with G = 761µm.

III. RESULTS AND DISCUSSIONS

A standard THz-TDS setup was used to characterize the transmission properties of the InSb waveguide. THz radiation is incident on input port and exits through output port as shown in Fig 1(a). Transmitted THz waveforms through the waveguides without stubs (reference) and with stubs (sample) are acquired and their FFT spectra are computed numerically. The ratio of sample and reference spectra is defined as transmission coefficient. Fig 1(b) shows the amplitude of transmission coefficient of InSb waveguide with width G = 740 µm and stub length L = 990 µm. Fig 1(b) shows a sharp resonance dip for waveguide with stub compared to the waveguide G = 761 µm without stub. At the resonance frequency the THz wave bounces back and forth inside the stubs like the Fabry Perot resonance resulting in transmission minimum [5]. At frequencies away from the resonant frequency, the electromagnetic wave experiences very small impedance mismatch at the waveguide-stub joints and, hence, propagates freely towards the exit of the waveguide resulting in high transmission. Further, it is also seen that the magnitude of electric field in the stubs is very small at off-resonant frequencies [5]. This resonance property of our device has been used for sensing the presence of any material loaded into the stubs.

Bovine Serum Albumin (BSA) is a well studied protein molecule and was chosen to study the sensing characteristics of the InSb waveguide device. Experiments were performed to measure the THz transmission of the device when loaded with a solution of the protein molecule BSA in deionised water at various concentrations.

Few micro litres of the prepared BSA-W solution was dropped into one of the stubs, thereby changing the refractive index of the medium inside the stub as shown in Fig. 2 (inset). The effective absorption coefficient (α_{eff}) as a function of linear frequency (*f*) of the measured spectra is defined [8] as,

$$\alpha_{eff}(f) = -\frac{1}{W}\ln\frac{E_{sample}(f)}{E_{ref}(f)}$$

THz transmission measurement with DI water in the stub of width W ~ 740 µm is considered as a reference, E_{ref} and sample spectrum, E_{sample} measurements carried out with 0.5mg/ml or 1mg/ml of BSA concentrations to determine $\alpha_{eff}(f)$ of BSA. THz transmission measurement with empty waveguide (air) is considered as reference E_{ref} to determine $\alpha_{eff}(f)$ of DI water.

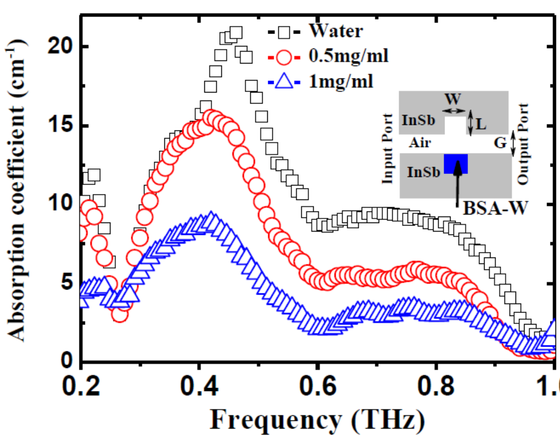

Fig.2. The calculated absorption coefficient vs. frequency of BSA-W solution measured by THz-TDS using InSb waveguide with stubs. Inset: Schematic of the designed InSb THz waveguide of L=990µm, W=G=740µm. The incident THz signal is coupled from the input port and the transmitted THz signal is detected at the output port.

Before each sample measurement, transmission of THz beam in the InSb waveguide and with stub filled with DI water (reference) was measured. All measurements were repeated to observe the consistency in the results. As the BSA-W concentration increases, the number of absorbing bulk water molecules decreases, leading to decrease in $\alpha_{eff}(f)$. The decrease in $\alpha_{eff}(f)$ with the increasing concentration of the BSA molecules is consistent with the reported [6, 8] results.

We determined the sensitivity of the sensor by noting the decrease in the absorption coefficient with increasing concentration of BSA. The plot of the decrease in the absorption coefficient, at 0.45 THz, versus the concentration of BSA is shown in Fig 3, where the graph for water corresponds to zero concentration of BSA. The data points indicate a linear fit over the range of concentration used in our experiments. The slope of the graph yields a sensitivity of about 13cm^{-1}/mg.

Thus, a minute change in the concentration of the solution, changes the refractive index sensed by the stub filled with BSA-W. Water completely attenuates THz radiation. Dissolving proteins molecules in water, in bulk quantity and studying their THz properties is a formidable task. Dropping only a micro liter quantity of BSA-W solution in the stub and being able to detect the BSA-W concentrations with high sensitivity is a very substantial improvement over this problem.

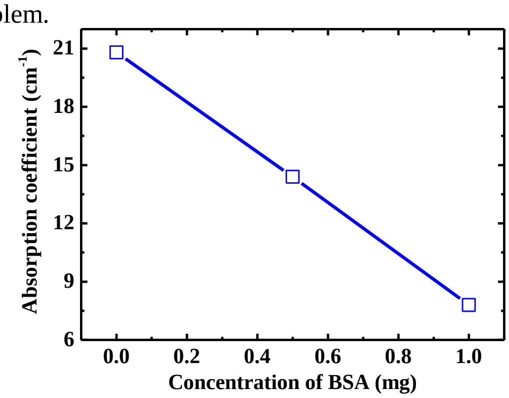

Fig.3. Calculated Absorption coefficient versus concentration of BSA. Slope of the linear fit gives a sensitivity of 13cm-1/mg.

This characteristic of the InSb waveguide demonstrates the promising sensing capability of the device to function as a THz-bio sensor. A minute change in the concentration of the medium and even a micro liter quantity inside the stub shows prominent change in the calculated absorption coefficient, thereby making InSb waveguide, a promising candidate for THz sensing.

In conclusion, the InSb waveguide-stub device may be exploited to sense a minute quantity of a biomaterial like BSA at THz frequencies.

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