Hyperbolic metamaterials for midinfrared sensing

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Large surface area Al-doped ZnO hyperbolic metamaterials for mid-infrared absorption spectroscopy applications

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Mid-infrared (Mid-IR) light between 2.5-20 µm offers a unique advantage in biochemical sensing due to characteristic absorption futures of target molecules in this wavelength region [1],[2]. The challenge is to detect low trace amounts of analytes due to the three orders of magnitude mismatch in sizes between Mid-IR wavelengths and molecules, resulting in weak absorption features of light.

The light absorption can be enhanced by implementing structures with a large surface area such as deep trenches, holes etc. Another, more peculiar approach is to use artificially designed materials with indefinite dispersion relation [3]. These are so-called hyperbolic metamaterials (HMMs), which are the class of strongly anisotropic artificial structures having their dielectric tensor components, the ordinary ($\varepsilon_o$) and extraordinary ($\varepsilon_e$) permittivity with opposite signs.

Recently, successful fabrication and optical characterization of large-area (2×2 cm²), high aspect ratio AZO pillar- [4] and trench-based metamaterials [5] with the enlarged surface area have been realized.

Here, we report the enhancement of absorption in HMMs composed of high aspect ratio Al-doped ZnO (AZO) nanotrenches [6]. AZO is an alternative plasmonic material operating at the Mid-IR frequencies [7] with the possibility to tune optical response by adjusting the doping level for optimal sensitivity of molecules on demand.

High aspect ratio AZO trenches have been fabricated by means of deep-UV lithography, atomic layer deposition (ALD) and several dry etch techniques. The fabrication procedure is based on ALD deposition of AZO on sacrificial Si template with the sub-sequential removal of Si. The process is fully compatible with large-scale CMOS technology. The cross-sectional SEM image of the final structure is shown in Figure 1 (a). The inset depicts the hyperbolic regime at the wavelength above 2.7 µm.

The sensing ability of AZO trench HMM has been demonstrated by depositing 5 nm SiO₂ layer around the trenches using ALD in order to emulate the presence of organic molecules. The inset in Figure 1(a) presents a schematic illustration of AZO HMM architecture conformally covered with a SiO₂ layer, which has a characteristic absorption peak around 8 µm due to phonon absorption. The reflection measurements were performed over a wavelength range from 6 to 10 µm with TM polarized light at $\theta=12^\circ$ angle of incidence. The AZO HMM covered with 5 nm SiO₂ exhibit a clear absorption as shown in Figure 1 (b). In order to highlight the enhancement, Figure 1 (c) presents the reflection difference of samples with and without SiO₂. The difference in reflection is as high as 9.4%.

The absorption enhancement is achieved by a combination of large surface area of HMM structure and interaction of bulk plasmon modes propagating in the trenches. Since the structure is composed of multiple high aspect ratio (1:6.7) sub-wavelength AZO trenches on Si substrate, it provides 14.5 times more surface area for residing analyte molecules compared to the flat surface. Additionally, the incident light is known to invoke and interact with the bulk plasmon modes in HMM trench structure [5]. These facts play a pivotal role in the phenomenon of absorption enhancement. Our estimation is 5.7% of enhancement is due to the surface effects and the rest 3.7% to bulk plasmon contribution. We conclude that such plasmonic metamaterial structures can be designed to detect traces of target molecules in Mid-IR spectroscopy.

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Figure 1. (a) Bird-eye-view SEM image of the fabricated AZO trench HMM, with permittivites shown by axis. The inset shows ordinary and extraordinary permittivites as a function of the wavelength and schematic illustration of AZO trench covered with 5 nm SiO₂. (b) TM reflection from the structure with and without 5 nm SiO₂ at the incident angle of 12°. (c) Reflection difference demonstrating absorption enhancement above 9%. Color shade represents an error bar.