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Published in:
Optical Sensors 2018

Link to article, DOI:
[10.1364/SENSORS.2018.SeW2E.5](https://doi.org/10.1364/SENSORS.2018.SeW2E.5)

Publication date:
2018

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Shkondin, E., Repän, T., Lavrinenko, A., & Takayama, O. (2018). Aluminum-doped Zinc Oxide Trench Hyperbolic Metamaterial as a Mid-infrared Sensing Platform. In *Optical Sensors 2018* Optical Society of America (OSA). <https://doi.org/10.1364/SENSORS.2018.SeW2E.5>

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Aluminum-doped Zinc Oxide Trench Hyperbolic Metamaterial as a Mid-infrared Sensing Platform

Evgeniy Shkondin, Taavi Repän, Andrei V. Lavrinenko, Osamu Takayama

ADTU Fotonik – Department of Photonics Engineering, Technical University of Denmark, Ørstedes Plads 343, DK-2800 Kgs. Lyngby, Denmark
Author e-mail address: alav@fotonk.dtu.dk

Abstract: We demonstrate enhancement of infrared absorption of 5 nm thick silica layer in nanotrench structures that function as hyperbolic metamaterials. Such structures can serve as a highly sensitive platform for mid-infrared absorption spectroscopy. © 2018 The Author(s)

OCIS codes: (250.5403) Plasmonics; (160.4760) Optical properties; (160.3918) Metamaterials; (220.4241) Nanostructure fabrication; (280.4788) Optical sensing and sensors

The mid-infrared (IR) spectroscopy in the wavelengths region between 2.5 - 25 μm (4000 – 400 cm^{-1}) is a powerful tool to detect molecules and chemical bonds due to their particular absorption bands in this range [1-3]. It enables a variety of potential applications from gas sensing for environmental monitoring to medical and clinical diagnoses. However, due to the huge mismatch between the mid-infrared light wavelength and analyte molecules dimensions, which are typically on the order of several nanometers, it is challenging to detect very trace amounts of molecules by detecting their absorption signatures.

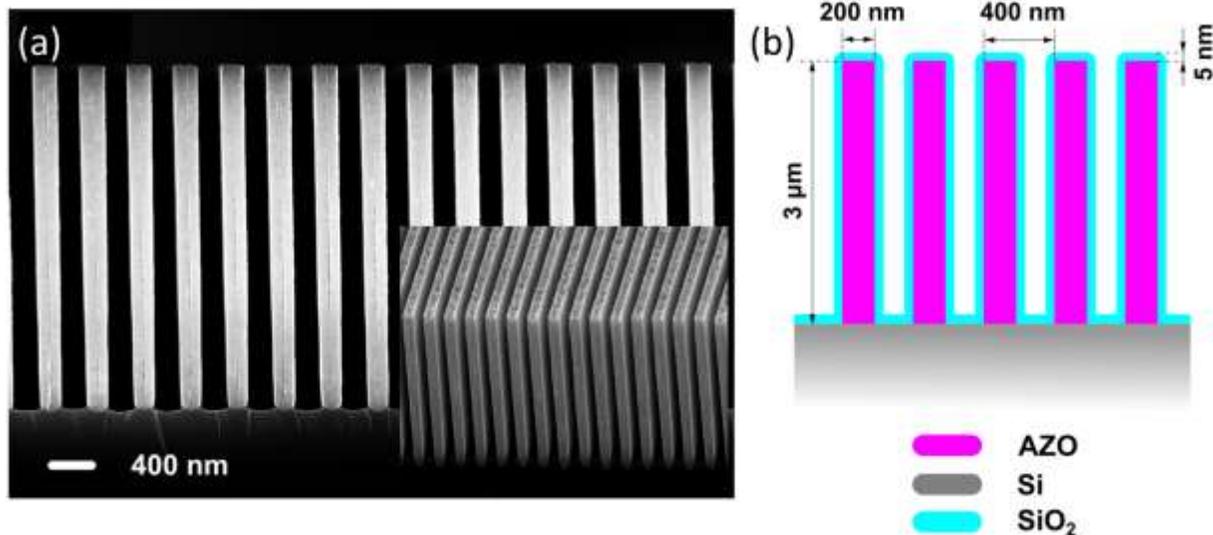


Fig. 1. (a) Cross-sectional SEM images of AZO-based HMM structures and bird's eye view of the structures. (b) A schematic illustration of AZO trench structures with 5 nm thick SiO_2 .

Hereby we report the use of hyperbolic metamaterials (HMMs) based on aluminum-doped zinc oxide (AZO) nanotrench structures as a sensing platform for the enhancement of molecular absorption of mid-IR light. HMMs are artificially designed structures that possess unusual indefinite dispersion in a certain region of frequencies and exhibit the hyperbolic shape of the isofrequency contours in the wavevector space [4]. AZO exhibits a plasmonic response, possessing a negative real part of the permittivity in the near- and mid-IR wavelength regions [5-7].

The structures are composed of multiple high aspect ratio (1:6.7) sub-wavelength AZO trenches on a Si substrate, Fig.1(a), providing 14.5 times more surface area for residing of analyte molecules than the flat surface. The whole structure is fabricated by the combination of deep UV lithography, dry etching, and ALD technique for AZO deposition, resulting in the uniform formation of deep trenches on a large scale area ($2 \times 2 \text{ cm}^2$). The fabrication process for the trench structures is fully compatible with the large-scale CMOS technology. Such AZO trench HMM structures support both surface waves and bulk plasmon waves in the broad wavelength range in mid-IR [7].

Here we exploit the bulk plasmon waves for enhancement of mid-IR light absorption by molecules. In order to demonstrate the potential of the trench HMMs for sensing we coat the trench structure with a 5 nm thick SiO₂ layer by ALD, emulating the presence of an analyte as illustrated in Fig. 1(b). The SiO₂ layer exhibits strong phonon absorption around 8 μm wavelength. As shown in Fig. 2(a), we measured free-space reflection of the samples with and without a 5 nm SiO₂ layer in the mid-IR wavelength range of 6.25 – 10 μm (1600 – 1000 cm⁻¹). The reflection difference yields over 9 % as shown in Fig. 2(b) [8]. The enhanced absorption is achieved by the two factors: interaction of bulk plasmon modes propagating in the trenches with the analyte silica layer and profoundly extended surface area of the trench structure with the fixed footprint.

In conclusion, the AZO trench structure exhibits broadband HMM performance in the range of wavelengths important for molecular sensing. Moreover, the doping level of AZO can be changed to adjust its plasmonic properties for desired wavelengths, leading to the optimum sensitivity of molecules on demand. Our demonstration shows that such structures can be effectively designed to detect traces of a target analyte and molecular sensing in mid-IR spectroscopy.

This work was supported by Villum Fonden "DarkSILD project" (11116) and Direktør Ib Henriksens Fond, Denmark. The authors would like to acknowledge the support from the Danish National Center for Micro- and Nanofabrication (DTU Danchip).

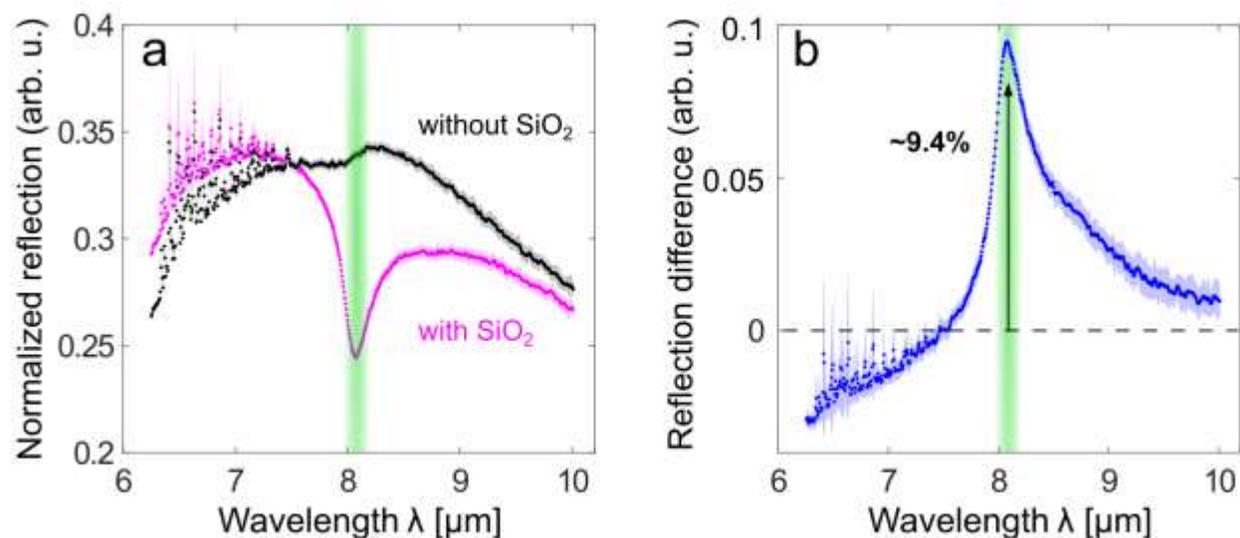


Fig. 2. (a) Measured free-space reflection of AZO trench structures with (dotted pink) and without (dotted black) 5 nm thick SiO₂ layer. (b) Reflection difference. The angle of incidence is $\phi = 12^\circ$ with TM-polarized incidence light for all reflection measurement. Colored shade represents an error bar.

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