

A Nanophotonic Fiber-Tip Sensor for the Detection of Single Nanoparticles

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Summary:

We present a nanophotonic fiber-tip sensor with an unprecedented combination of quality factor, reflection modulation, and mode confinement by using advanced design methods. Due to this unique combination it allows for the detection of nanoscale objects, where we experimentally demonstrate the real-time detection of single 50 nm nanoparticles.

Keywords: Nanophotonics, Photonic Crystal Cavities, Fiber-Optic Sensors, Fiber-Tip Sensors, Nanoparticles

Introduction

Fiber-optic sensors allow for accurate and remote sensing of the properties of the surrounding medium while being minimally invasive and insensitive to electromagnetic interference. The most common fiber-optic sensor, the fiber Bragg grating (FBG), relies on the periodic modulation of the core of the fiber. FBGs are typically only sensitive to temperature and strain. To increase the functionalities of fiber-optic sensors, many types of “lab-on-fiber” technologies have been proposed and investigated, which combine a local resonant structure in or on the facet of an optical fiber [1,2]. Generally, fabrication methods for micro- or nanostructures on the tip of a fiber lack scalability and flexibility. However, recently, our group developed a wafer-to-fiber transfer technique where a suspended nanopatterned semiconductor membrane is defined and transferred to the fiber through a hole etched in the substrate [3]. Using this membrane-on-fiber technology, photonic crystals (PhCs) based on guided mode resonances were placed on top of a fiber. These designs have a relatively low quality factor and delocalized field distribution, which limit their sensing performance. In this work, we demonstrate that placing a photonic crystal cavity (PhCC) on a fiber-tip is possible. Using advanced design techniques we experimentally show fiber-tip sensors with quality factors in the order of multiple 1000s, tightly confined modes with $V_m=0.72 (\lambda/n)^3$, and efficient coupling with standard single mode fibers (SMF-28). This

results in the highest Q/V ratio of any fiber-tip sensor with the added benefit of efficient coupling resulting in a large reflection modulation. An example of the fiber-sensor can be seen in Fig. 1. We demonstrate the practical use of the sensor in the real-time detection of single nanoparticle, which is made possible due to the highly localized mode. We specifically show the real-time detection of single 50 nm polystyrene particles.

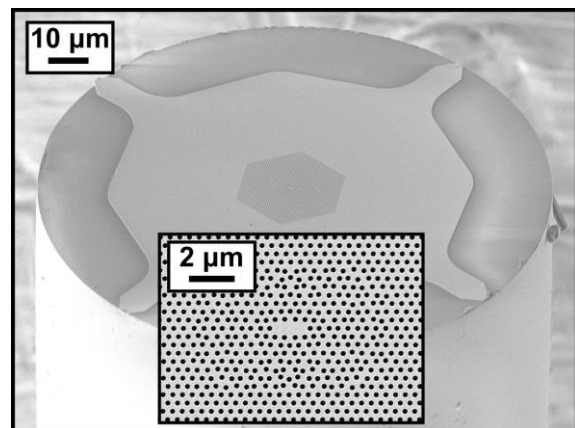


Fig. 1. Scanning electron microscope (SEM) image of the nanophotonic fiber-tip sensor. Inset: zoom-in of the optimized cavity.

Simulations

The main challenge for fiber-tip PhCCs is the spatial and angular mismatch with the fiber mode, leading to poor coupling efficiency. The PhCC radiation pattern can be controlled by repositioning a subset of holes and defining a subharmonic lattice [4], referred to as gentle

confinement and bandfolding respectively. In this work we make use of an open-source gradient-based optimization method based on guided mode expansion (GME), which alters the hole position surrounding the cavity to improve an objective function [5]. Here, we optimize the quality factor, the efficiency, and the mode volume. After optimization the result is simulated in the finite element method (FEM) software *COMSOL Multiphysics*. For our case the coupling efficiency increased from $\eta=0.008$ to $\eta=0.126$, while simultaneously increasing the quality factor from $Q=1850$ to $Q=4400$.

Characterization

The PhCCs were fabricated with standard semiconductor nanofabrication techniques and transferred to the facet of optical fibers using the approach described in Ref. [3]. For the PhCCs on fiber-tips we routinely obtain sensors with Q-factors in the multiple 1000s in combination with coupling efficiencies over 10%. This corresponds in a fiber-tip sensor with one of the highest Q/V ratios with considerably larger reflection modulations compared to other demonstrated fiber-tip sensors.

Sensing

Due to its narrow line width and high reflection modulation, the optimized PhCC on fiber-tip can be used as a precise sensor for multiple parameters. Here, we demonstrate two applications: refractive index (RI) sensing and single nanoparticle sensing.

Fiber-tip RI sensors have applications for in-line sensing and remote monitoring where the composition in (bio)chemical processes can be assessed, with the benefit of having an extremely small footprint. Furthermore, when adopting proper surface functionalization techniques RI sensors can be used for the specific detection of biomarkers. By dipping the fiber-tip sensor in solutions of deionized water (DI) and isopropanol (IPA) with a range of mixing ratios, we obtain a sensitivity of $S_n=79$ nm/RIU with a limit of detection of $LoD=3\sigma_n/S_n=4.5 \cdot 10^{-6}$ RIU.

Additionally, using the unique features of our nanophotonic fiber-tip sensor we are able to sense single nanoscale objects such as nanoparticles. Here, we use an aqueous suspension of positively charged amine-coated polystyrene particles ($n=1.56$) with a diameter of 50 nm. Using plasma cleaning the surface of the sensor is activated which results in negatively charged hydroxyl groups that lead to random adsorption of the nanoparticles on the surface due to electrostatic interactions. In Fig. 2 the resonant wavelength shift as a function of time can be seen in the top graph and the differential shift can be seen in the bottom graph. Multiple

discrete red-shifts are observed which are attributed to the binding of single 50 nm particles [6].

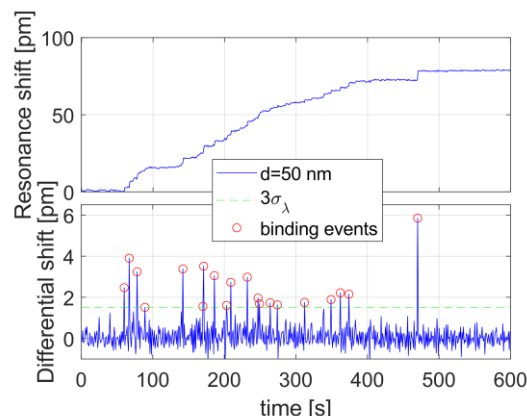


Fig. 2. Resonant wavelength shift (top) and differential shift (bottom) over time of binding of 50 nm particles on the PhCC fiber-tip sensor.

Conclusions and outlook

In this work, we showed a fiber-tip sensor with an unprecedented combination of quality factor, reflection modulation, and mode confinement. We demonstrated that this sensor can be used to detect single nanoparticles down to 50 nm in diameter. The proposed sensor has immediate applications in biosensing, industrial sensing, and air-quality monitoring. By using suspended structures and high-NA fibers, nanophotonic cavities with best-in-class characteristics can be realized with applications from single-photon emitters to nano-optomechanical sensors.

References

- [1] A. Ricciardi et al., Lab-on-Fiber Technology: a new vision for chemical and biological sensing, *Analyst* 140, 8068 (2015); doi: 10.1039/C5AN01241D
- [2] M. Pisco and A. Cusano, Lab-on-Fiber Technology: A Roadmap toward Multifunctional Plug and Play Platforms, *Sensors* 20, 4705 (2020); doi: 10.3390/s20174705
- [3] L. Picelli et al. Scalable wafer-to-fiber transfer method for lab-on-fiber sensing, *Appl. Phys. Lett.* 117, 151101 (2020); doi: 10.1063/5.0021701
- [4] N.V.Q. Tran et al., Vertical high emission in photonic crystal nanocavities by band-folding design, *Phys. Rev. B.* 82, 075120 (2010); doi: 10.1103/PhysRevB.82.075120
- [5] M. Minkov et al., Inverse Design of Photonic Crystals through Automatic Differentiation. *ACS Photonics* (2020); doi: 10.1021/acsp Photonics.0c00327
- [6] A.L. Hendriks et al., Detecting Single Nanoparticles Using Fiber-Tip Nanophotonics. *Optica* (2024); doi: 10.1364/OPTICA.516575 (in press)