Magnetically sensitive optical fiber probes with step index, suspended core or hollow core microstructures

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Abstract: Optical fibers with nitrogen-vacancy center-containing nanodiamonds are discussed for three approaches involving standard and hollow core microstructures. Magnetic sensing is demonstrated with the best sensitivity of 500 nT/sqrt(Hz) achieved for 24 cm long fibers.

Keywords: nitrogen-vacancy centers, nanodiamonds, optical fibers, magnetic field sensing

1. Introduction

Three series of optical fiber probes functionalized with nanodiamonds are discussed in scope of their development approaches and magnetometry performance assessment. Practical implementation of the nitrogen-vacancy spin state dynamics in diamond for magnetic field mapping requires management of the NV^{-} fluorescence collection. Application of optical fibers can answer this demand, but different strategies involving various diamond functionalization schemes are explored for maximization of the coupling efficiency of the NV^{-} fluorescence to the guided modes [1-4].

In scope of the work we demonstrated successful implementation of step-index, suspended core and hollow core fiber structures with sub-micron sized, NV^{-} diamonds localized inside and along the fiber core, as shown for each of the realized case in Fig. 1. The applied technological procedures of fiber development, as well as the proof-of-principle magnetic field sensing using optically detected magnetic resonance (ODMR) or direct magnetic field measurements are discussed in detail.

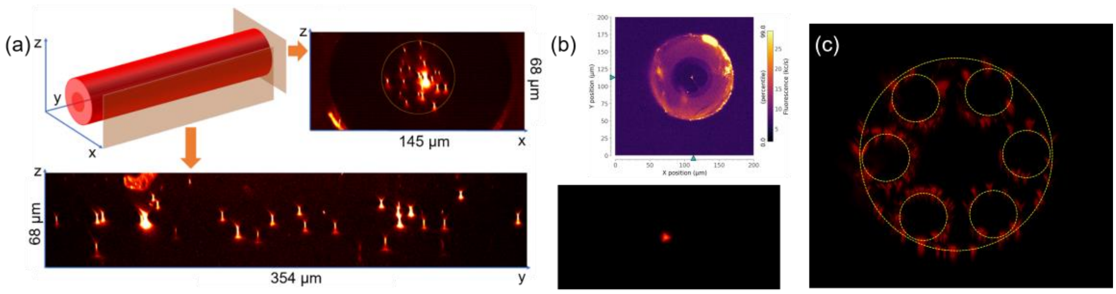

Figure 1 Images of the developed fibers obtained with confocal microscopy: (a) front-face and longitudinal scans of a step-index fiber, (b) suspended core fiber with nanodiamonds located centrally in the core: a confocal microscope image and a CCD camera image, (c) anti-resonant hollow core fiber with nanodiamonds suspension-coated inside the core.
Table 1 List of microscope objectives.

2. Conclusions

In the step index fiber the incorporation of NV— nanodiamonds into the fiber core is carried out using core nanostructuring, i.e. multiple stacking of hundreds of nanodiamond-coated glass canes. Careful adjustment of drawing conditions enabled fully fused core without air inclusions neither in the core nor at the core-cladding interface. Importantly, diamond particles agglomeration was largely avoided and uniform longitudinal and transverse plane diamond distribution was obtained. The developed suspended core fiber enabled strong confinement of the guided mode and spatial overlap of the diamond particles with the guided mode, due to the small difference between the core diameter of 1.5 µm and a typical nanodiamond size of 750 nm. Both fibers have been developed using standard materials and techniques, which means low unit cost in a possible application as a single-use items in bio-medical applications. Finally, we demonstrate an anti-resonant hollow core fiber with the inner surfaces of the core coated with the diamond particles. The fiber has broad transmission across the visible wavelengths and the possibility of integration with microfluidics systems.

The developed fibers have enabled measurements of optically detected magnetic resonance (ODMR) or direct magnetic field measurements with samples as long as 60 cm. Typical results are shown in Fig. 2. The optical readout contrast in the fiber end-to-end transmission mode (as opposed to side illumination and collection) was as high as 7% over a sample length of 24 cm in the suspended core fiber (and over 20% in the hollow core fiber). The corresponding magnetic sensitivity achieved with the probe was 500 nT/sqrt(Hz). This is a noticeable improvement in comparison to earlier demonstrations, in which fiberized magnetic field probes with fiber tip or taper functionalization were characterized with tens down to a dozen of µT/sqrt(Hz) magnetic sensitivity, while their NV fluorescence collection efficiency, usually not exceeding single percentages, was still strongly dependent on complicated mechanical apparatus realizing e.g. a scanning function over a limited detection area.

The demonstrated fibers open up further work directions, focused on for example on quasi-vector magnetic field sensing involving magnetic field gradient measurements.

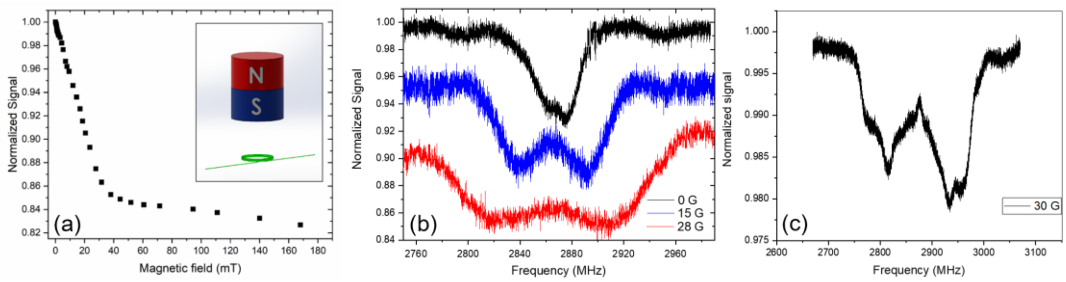

Figure 2 Magnetic field sensing with the developed fibers: (a) direct magnetic field measurements, a 60 cm long step-index fiber, (b) ODMR traces obtained with a 24 cm long suspended core fiber, (c) an ODMR trace obtained using the anti-resonant hollow core fiber.

Acknowledgments

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