Fluorescence-based flying-particle sensor in liquid-filled hollow-core photonic crystal fiber

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Abstract: We present a novel irradiation sensor based on a fluorescent microparticle that is optically guided inside the core of a liquid-filled photonic crystal fiber. We demonstrate irradiance measurements with spatial resolution of ~10 µm.

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1. Introduction

Fiber based irradiation sensors are of great interest in applications such as nuclear science, chemical engineering and medicine. Typically, the tip of an optical fiber is coated with luminescent material, whose luminescence is picked up by the fiber core. While this method enables detection across the electromagnetic spectrum, from UV to x-ray [1-3], it is limited to single-point detection, making spatially resolved measurements cumbersome. We recently introduced a new class of reconfigurable fiber sensor, based on a 'flying-particle' optically trapped inside a hollow-core photonic crystal fiber (HC-PCF) [4]. In a first demonstration, the electric field distribution near the surface of a multi-element electrode was measured with a resolution of ∼100 µm by monitoring changes in the transmitted light signal due to the transverse displacement of a charged silica microparticle trapped within the hollow core. We also proposed that, by using fluorescent or radioluminescent microparticles, it would be possible to resolve irradiation profiles with high positional accuracy over long distances [4]. Here we give the first experimental demonstration of such a 'flying-particle' irradiation sensor, by monitoring the emission from fluorescent microparticles that are optically guided along a water-filled HC-PCF.

2. Experimental set-up

A schematic of the experimental set-up is shown in Fig. 1(a). A procedure similar to that described in [5] is used to launch a 3 µm diameter fluorescent polystyrene microsphere into a 25 cm long water-filled hollow-core kagomé-PCF with a core diameter of 21.5 µm. Once inside fiber, the particle is propelled by a titanium sapphire (Ti:Sapph [two p's!]) laser operating at 785 nm, while its position is monitored by Doppler velocimetry [6]. The fiber loss at this wavelength is ~20 dB/m and is caused by water absorption rather than waveguide loss. The typical guidance velocity was 125 µm/s for a guided optical power of 100 mW. At one position, the fiber is transversely illuminated by a weakly focused laser diode operating at 532 nm, near the excitation peak of the fluorescent dye (λ_{ex} = 542 nm). When the particle passes this region, part of its fluorescence (peak at λ_{em} = 612 nm) is coupled to the PCF modes and guided to the fiber end, where it is filtered and detected by a photodiode (PD 2). The fiber loss at this wavelength is estimated to be ~10 dB/m.

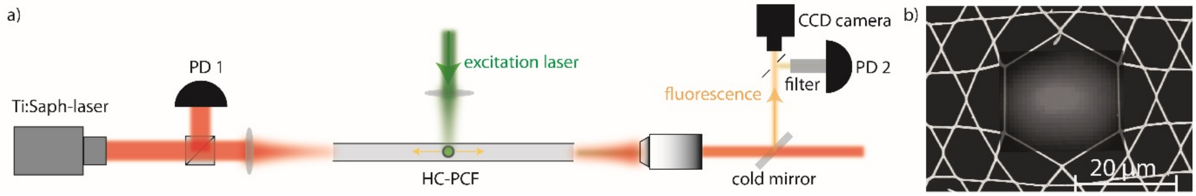

Fig. 1 a) Schematic of setup. A fluorescent particle is optically propelled along the HC-PCF. Fluorescence from the particle is guided to the fiber end, filtered, and detected by a sensitive Si photodiode (PD 2). The position of the particle is obtained by Doppler velocimetry using back-scattered light detected by photodiode PD 1. b) A scanning electron microscope image of the kagomé-style hollow-core PCF with a superimposed core mode at 785 nm.

3. Experimental results

Figure 2(a) shows the fluorescence signal detected as a function of particle position. The observed peak in fluorescence is accurately approximated by a Gaussian function with half-width *w* = 37.5 µm. The maximum output voltage of the sensor (inset) is proportional to the irradiance intensity, confirming that the response is linear. The fluorescent signal reaching the detector was estimated to be 10 pW, for an excitation irradiance of 100 W/cm^2.

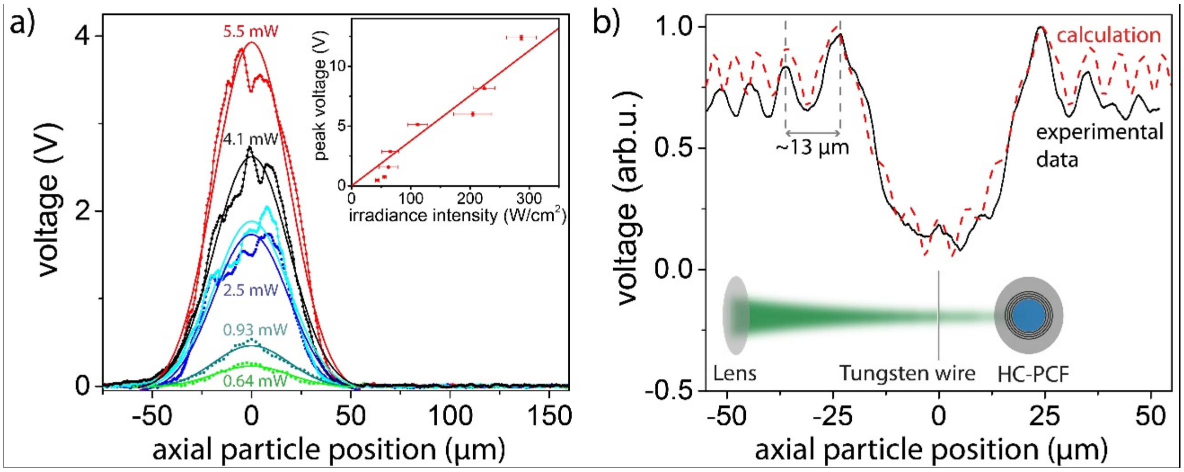

Fig. 2 a) Detected fluorescence signal as a function of particle position for different optical powers. (inset) The peak height is roughly linear with the irradiation intensity. b) Detected diffraction pattern from a metallic wire with a diameter of 26 µm, placed 100 µm away from the HC-PCF. The experimental data (black, solid curve) is in good agreement with the calculated intensity profile (red, dashed curve).

To estimate the spatial resolution of the sensor, a small length of the PCF was blocked by a tungsten wire of diameter 26 µm. The measured irradiance distribution is shown in Fig. 2(b), and is in good agreement with analytical diffraction theory for a cylindrical wire [7]. The slight discrepancy for higher-order diffraction peaks may be explained by refraction in the cladding structure, which was not taken into account in the calculation. Nevertheless, the observed irradiance profiles demonstrate that features as small as ~10 µm can be resolved.

4. Conclusions

Fluorescent microparticles, optically guided inside the core of a HC-PCF, can remotely detect irradiation with a spatial resolution of ~10 µm, ultimately limited by the size of the particle. The spectral response can be conveniently adjusted using microparticles with different luminescence properties, with potential applications in the detection of x-ray and nuclear radiation. The maximum fiber length in the current configuration is limited by water absorption to about ~1 m, but can be easily extended to several meters by shifting the guidance laser to shorter wavelengths, or by performing the experiment in an evacuated fiber.

5. References

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