Photonic crystal fiber–based dual-modality probe for simultaneous sensing and imaging applications

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Abstract. A dual-modality fiber scope probe that can simultaneously obtain the spectroscopic signature and images is proposed and illustrated. The photonic crystal fiber and micro CCD camera form the probe distal end. A preliminary experimental investigation using the developed probe has been carried out on phantom tissue stained with fluorophores. Both hollow-core and double-clad photonic crystal fibers have been used at the distal end in separate embodiments, and their collection efficiencies are compared. This proposed probe and methodology are expected to find potential biomedical diagnostics applications. © *2009 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3250294]

Subject terms: double-clad photonic crystal fiber; hollow-core fiber; fiber probe; fluorescence; imaging; sensing; microcamera.

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1 Introduction

For biomedical applications, optical sources in the visible, ultraviolet, near-infrared (NIR), and mid-infrared are employed.[1] This wide range of electromagnetic spectrum must be transmitted from the source (either a laser or a superluminescent diode) to the tissue by a device that makes the manipulation of the optical beam in a medical intervention easier. The development of a flexible endoscope was possible due to the incorporation of optical fibers. Also, the ease with which fiber probes can be incorporated into current technology such as endoscopes makes it ideal for use in clinical environments as well.[2,3] Then measurements can be taken in a minimally invasive way using endoscopes with optical fibers; the diagnosis is immediate, and response to treatment can be also monitored.

The current fiber-optic probe configurations are mostly based on conventional silica fibers that guide light by total internal reflection. The high excitation efficiency of the single-mode fibers (SMFs) has made them the most common type of fibers in fiber-optic imaging systems.[4] In general, the core diameter will be small in conventional single-mode fiber. Additionally, the low numerical aperture (NA) of an SMF limits its ability for signal collection. Over the past decade, a new type of optical fibers known as s (PCFs) has been developed.[5]

The photonic crystal fiber technology offers new types of fiber with large mode area (LMA) and endless single mode by accurately controlling the hole size and distribution.[6] In LMA-PCFs, the core diameter can be as large as 35 μm with single-mode guidance for any wavelength at which silica is transparent. The larger mode area makes it possible to transmit high power levels through the fiber without causing nonlinear effects or material damage. But the low NA of these types of fibers reduces the collection efficiency, which limits its application. Another class of photonic crystal fiber, known as hollow-core fiber, in which air holes form a periodic pattern resulting in a two-dimensional (2-D) photonic crystal, can confine light to the core region even when the core region has lower refractive index than the cladding material.[7] The zero-dispersion wavelength of the hollow-core fiber can be shifted from the conventional 1310 nm (zero-dispersion wavelength for bulk silica) to a shorter wavelength, such as 800 nm or down to a visible wavelength. The background signal originating from the core material is suppressed by guiding the excitation beams through the air core.[8] By replacing the conventional SMF with the hollow-core PCF, much improvement of two-photon fluorescence excitation efficiency and image quality are achieved due to negligible nonlinear effects at the near-zero dispersion wavelength of this hollow-core PCF.[9] But the lower NA limits its application in endoscopy.

The double-clad fiber is another type of PCF, where the central single-mode core is surrounded by a lower index cladding region that is further surrounded by a region of even lower refractive index so that light can be confined and propagated. The LMA core of the fiber is placed in a microstructured inner cladding, offering the single-mode guidance for NIR beam and reducing nonlinearity significantly for excitation. The inner cladding has a high NA up to 0.6 and a diameter of hundreds of micrometers to propagate light in visible and NIR wavelength ranges with a high efficiency. With its unique properties—the single-mode central core and the high NA multimode inner cladding—the double-clad PCF has gained attention in the research for improvement in signal level in the fields of biosensing and endoscopy.[10,11] The use of an optical fiber having double cladding allows us to guide the excitation beam through the small-diameter conventional core of a fiber and to subsequently collect the excited fluorescence light signal using the larger diameter inner cladding of the same fiber. The

application of double-clad PCFs in a nonlinear optical microscope has been demonstrated to improve the detection efficiency significantly by two orders of magnitude compared to that achieved by a standard SMF.[12] Due to small diameter of the fiber, it can be easily incorporated into the existing endoscopy equipment.

Optical imaging, being minimally invasive compared to the conventional methods like surgery or biopsy, is of major interest in disease diagnosis, such as the detection of cancerous growth in the gastrointestinal path.[13,14] The integration of a microcamera with a high-resolution CCD to the existing endoscopes has exposed interesting research areas since it promises endoscopes with smaller diameters for visualizing hard-to-access areas. In this context, this paper proposes and illustrates a dual-modality diagnostic methodology that explores the properties of double-clad PCF and microcamera with a coupled diode-pumped solid-state (DPSS) laser as the excitation source. This design is expected to permit quantitative measurement of fluorophore concentration and also to minimize the need for expensive and time-consuming tissue-extraction or labeling methods.

2 Experiment

2.1 *Comparison of Collection Efficiencies of Hollow-Core and Double-Clad PCF*

The performance of two different types of PCFs double-clad and hollow-core, for beam delivery/collection have been analyzed. In a single-fiber-based fluorescence probe, the effective fluorescence detection volume from a region adjacent to tip of the fiber is determined by both its illumination and its collection volumes. For a particle to be detected at a given point, it has to become excited, and simultaneously a photon emitted from this point has to be collected by the same fiber. The hollow-core PCF guides light in a hollow core by means of a photonic band-gap effect achieved using a holey structure around the core. These fibers guide light in a single mode with greatly improved power delivery compared to conventional single-mode fibers.[15] Double-clad fibers are characterized by a central single-mode core surrounded by an inner and an outer cladding region. Here, the excitation mode is single. The illumination intensity distribution adjacent to the tip of the flat cleaved fiber is assumed to be axis-symmetric. The probability of collection is given by the probability of a photon emitted from the sample reaching the fiber end, provided the angle of incidence is less than or equal to the maximum acceptance angle (α) of the fiber, where $\alpha = \sin^{-1}(NA/n)$, n denotes the refractive index of outside medium, and NA denotes the numerical aperture.

Figure 1 illustrates the efficient fluorescent collection in a double-clad fiber compared to the hollow-core fiber. Here, the single-mode core is surrounded by a larger NA outer core (also acts as cladding of the inner core) that can collect the emitted fluorescence. Since the fluorescent emission is assumed to be constant in every direction, the collection probability is proportional to a solid angle subtended by the area of intersection at the point where the particle to be detected is placed. Since a double-clad fiber can propagate light in the inner cladding region by total internal reflection, enhanced fluorescence collection is possible. The NA of the inner cladding is generally twice as large as that of conventional single-mode fibers. Thus, efficient fluorescence collection is possible in double-clad fiber along with single-mode excitation.

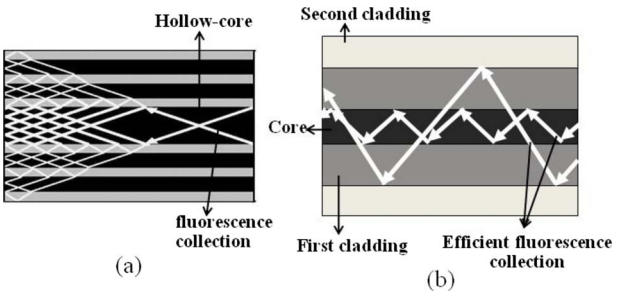

Fig. 1 Illustration of fluorescence collection in (a) a hollow-core PCF and (b) a double-clad PCF.

The diverging beam from a 473-nm DPSS laser (output power=10 mW) was collimated by a lens and was diverted to the fiber coupling unit (Newport F-91TS Coupler) using a pellicle beamsplitter (BS). The microscope objective (MO) lens (Newport M-20X, 0.4 NA) integrated with the FC coupler at the proximal end of a double-clad (DC-165/16-passive, crystal-fiber)/hollow-core PCF (Air-6-800, crystal-fiber) performs the illumination as well as the collection duties. The double-clad PCF has a core diameter of 16 μm, an inner cladding with a diameter of 165 μm, and an NA of 0.6 at wavelength 600 nm. Within the outer cladding region of 350 μm in diameter, a ring of air holes is used to efficiently guide and collect light in the pure silica multimode inner cladding. The hollow-core fiber has a core size of 6 μm, cladding diameter of 122 μm, and NA of 0.2. The scanning electron microscopy (SEM) images of the fibers under study are shown in Fig. 2.

The sample used is a phantom tissue (Simulab Corp.), stained with Green wop fluorescent dye. The source light is delivered to the sample surface from the probe distal end. The reflected and fluorescence light from the surface plane of the target specimen will be collected and focused at the hollow-core/double-clad PCF plane. A 20× objective lens with 20-mm working distance is placed at the proximal end of the probe, which collects the emitted light and is directed to the high quantum efficiency spectrometer using a pellicle beamsplitter. The large NA of the outer core in the double-clad PCF can enhance collection of emitted fluorescence when compared to the hollow-core fiber. The collected in-

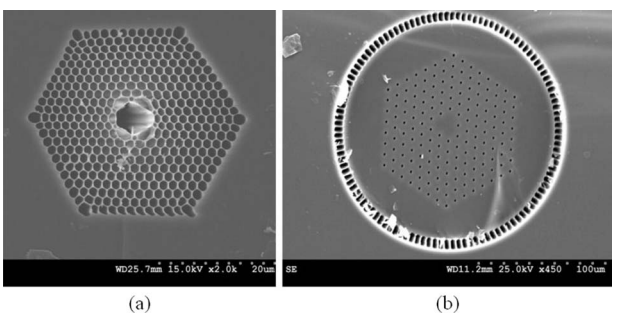

Fig. 2 SEM images of the (a) hollow-core and (b) double-clad PCFs used in the probe configuration.

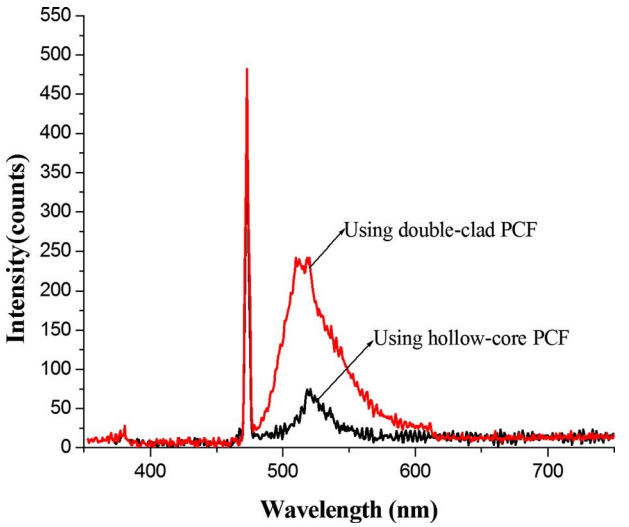

Fig. 3 Collected intensity spectra of Green wop dye using a hollow-core and a double-clad PCF-based fiber probe at constant illumination. (Color online only.)

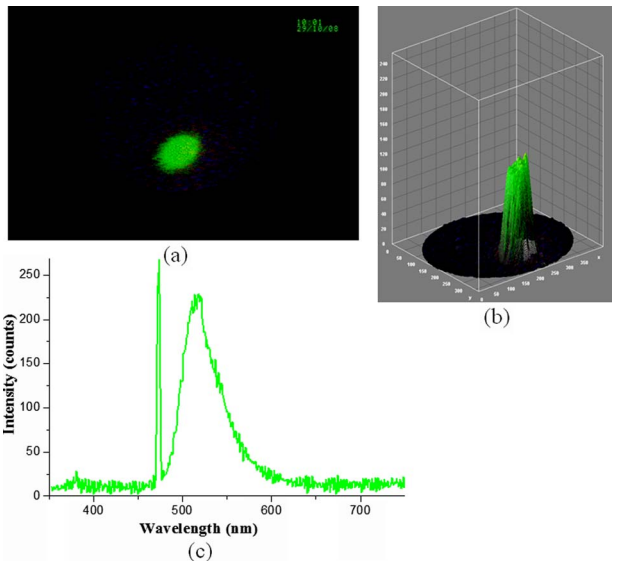

Fig. 5 (a) Spatial information (image); (b) corresponding interactive 3-D surface plot; and (c) spectrum of the phantom tissue sample stained with Green wop fluorescent dye. (Color online only.)

tensity spectra using these two fibers are shown in Fig. 3 for comparison. The collection efficiency of the double-clad fiber is found to be much higher than that of the hollow-core fiber.

Because of its better collection efficiency, we have employed the double-clad fiber in the proposed integrated dual-modality probe configuration (Fig. 4).

2.2 *Dual-Modality Probe*

Figure 4 shows the schematic of the proposed configuration of the dual-modality probe system. It mainly consists of (1) a DPSS laser operating in continuous-wave mode, (2) a fiberscope probe that contains a double-clad PCF and a microcamera (Medigus Ltd.). A high quantum efficiency spectrometer (QE65000), camera control unit, and computers form the display and the analysis unit.

The fiberscope probe has been configured with a distal end consisting of a double-clad fiber and microcamera. This type of arrangement allows easy plug-in and plug-out of the probe and the source. The 1.8 mm × 1.8 mm CCD camera includes a microcamera head that has high-quality optics and a shielded camera cable. The camera is found to

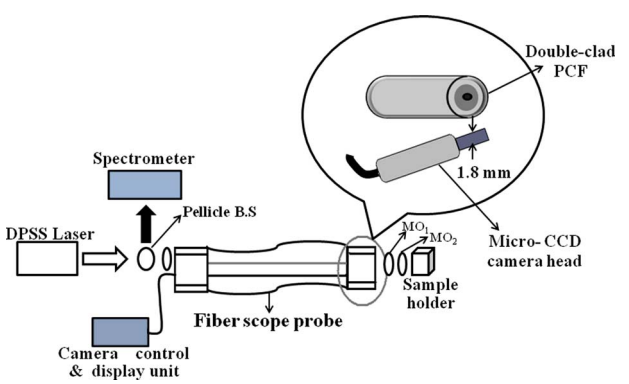

Fig. 4 Schematic of the developed integrated dual-modality probe.

be highly suitable for endoscopy imaging due to its small head size and its high performance. The phantom tissue sample stained with fluorescent dye is placed over a three-axis scanning stage, which acts as the sample holder. In our study, we have used Green wop and Red wop fluorescent dyes as the staining agents. The stage can be varied over a few centimeters with micrometer resolution, which effectively increases the scanning range of the fiber probe.

The DPSS laser (473 nm), which is diverted through a pellicle BS is coupled to the proximal end of double-clad fiber. The diverging beam emerging from the distal end of the image fiber was allowed to pass though the 2-f lens system, which is configured using two microscope objective (MO) lenses [Newport M-20X, 0.4 (MO_1) and Olympus UMPLAN FI 50X/0.8 (MO_2)]. The reflected and fluorescence light from the target specimen surface will be collected at the double-clad fiber, which can transmit light through the core as well as the inner cladding. This light is collected through an MO and is transmitted to a high quantum efficiency (QE 65000) spectrometer using a pellicle beamsplitter. The spectrometer displays the spectrum of the sample under study. Simultaneously, the image of the sample is obtained through the microcamera. The obtained image and spectra of the tissues stained with Green wop and Red wop fluorescent dyes are given in Fig. 5 and Fig. 6, respectively. The interactive 3-D surface plot of the obtained images is also given.

3 Conclusion

We have demonstrated a dual-modality probe to obtain an image and a spectrum from a sample simultaneously by exploring the properties of PCF and a micro-CCD camera. Both hollow-core and double-clad PCFs were incorporated in the probe configuration, and the collection efficiencies were compared. Then, a probe was designed with a distal end consisting of a highly efficient double-clad PCF and micro-CCD camera. The designed probe configuration has

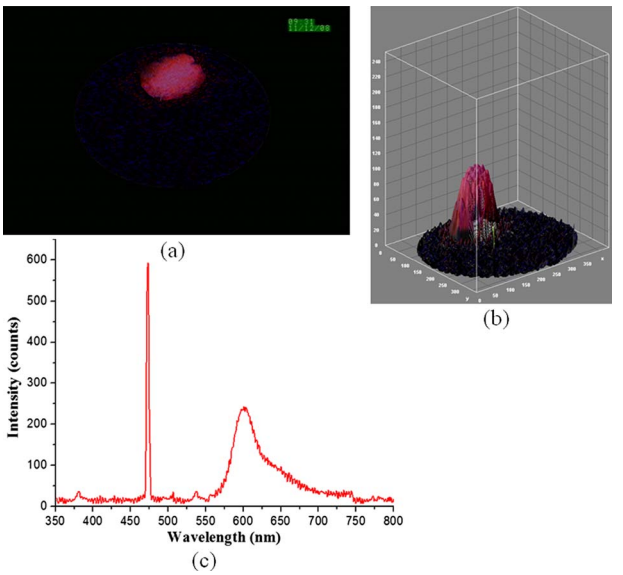

Fig. 6 (a) Spatial information (image); (b) corresponding interactive 3-D surface plot; and (c) spectrum of the phantom tissue sample stained with Red wop fluorescent dye. (Color online only.)

been used only in *ex vivo* conditions, where the sample was placed over an XYZ stage that allows an extremely large scanning range. The main advantage of the dual-modality approach is that it is capable of simultaneously acquiring both the spatial information (image) and the spectrum from the targeted tissue site. The incorporation of two modalities into a single fiber scope can increase the diagnostic accuracy and provide more favorable results. This proposed probe and methodology is expected to find potential applications in the area of biomedical diagnostics. Future works will be targeted on incorporating nonmechanical scanning approaches such as digital micromirror device (DMD)–based schemes for applications in *in vivo* diagnostics.

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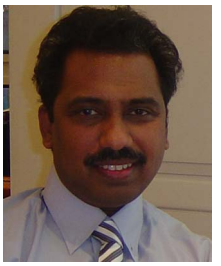

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