

Double-clad photonic crystal fiber coupler for compact nonlinear optical microscopy imaging

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A 1×2 double-clad photonic crystal fiber coupler is fabricated by the fused tapered method, showing a low excess loss of 1.1 dB and a splitting ratio of 97/3 over the entire visible and near-infrared wavelength range. In addition to the property of splitting the laser power, the double-clad feature of the coupler facilitates the separation of a near-infrared single-mode beam from a visible multimode beam, which is ideal for nonlinear optical microscopy imaging. In conjunction with a gradient-index lens, this coupler is used to construct a miniaturized microscope based on two-photon fluorescence and second-harmonic generation. Three-dimensional nonlinear optical images demonstrate potential applications of the coupler to compact all-fiber and nonlinear optical microscopy and endoscopy. © 2006 Optical Society of America

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Since their inception in the early 1990s, photonic crystal fibers (PCFs) have revolutionized fundamental research on and development of optical fibers.¹ The superiorities of PCFs, such as endless single-mode operation, dispersion engineering, and high nonlinearity have led to a broad range of applications, including the development of high-power fiber lasers.² In addition, double-clad PCFs made of pure silica have attracted research in biosensing and bio-imaging to improve the system efficiency because of their dual function of single-mode and multimode delivery through the central core and the inner cladding region of high numerical aperture (NA), respectively.³⁻⁶ The detection efficiency of the nonlinear optical microscopy system based on the double-clad PCF is approximately 2 orders of magnitude higher than that based on a standard single-mode fiber.⁵ Although the dual function of the double-clad fiber makes miniature and flexible microendoscope probes possible, a further compact imaging system could be achieved by use of a multiport fiber coupler to achieve self-alignment and replace bulk optics for an all-fiber microscopy system.⁷⁻⁹

Recent theoretical studies and fabrication of PCF couplers have been reported for a number of PCF structures.¹⁰⁻¹³ However, there has been no report on the fabrication and application of double-clad PCF couplers. The difficulty in fabricating a double-clad PCF coupler is to achieve mode coupling through two clad regions and to preserve the single-mode and multimode guidance in the core and the inner clad regions, respectively. In particular, for applications in nonlinear optical microscopy, one arm of the double-clad PCF coupler should permit the single-mode propagation of a near-infrared laser beam in the core, while the other arm can facilitate the multimode collection of the visible nonlinear optical signal. While the side-polished method has been used to produce a PCF coupler with single-mode tuneable splitting ratios,¹² the fused tapered method has been successful in generating single-mode and multimode air-silica PCF couplers according to the principle of mode expansion.^{11,13} In this Letter we report the fabrica-

tion of a three-port double-clad PCF coupler fabricated by the fused tapered method, showing the single-mode and multimode separation at different wavelengths. A compact nonlinear optical microscope is implemented by use of this coupler and a gradient-index (GRIN) lens, demonstrating high-resolution three-dimensional two-photon fluorescence and second-harmonic generation (SHG) images.

The double-clad PCF we used for fabricating a coupler (Crystal Fiber A/S) has a core diameter of $20 \mu\text{m}$ and an inner cladding with a diameter of $165 \mu\text{m}$, as shown in the left-hand inset of Fig. 1. Air holes with a hole-to-hole pitch ratio of 0.26 surround the central core, which can provide single-mode delivery in the near-infrared wavelength region. A ring of air holes is used to confine the multimode propagation of light in the inner cladding with a NA of 0.6 at the wavelength 800 nm. Since the fused taper method facilitates the coupling of single-mode and multimode fibers,^{11,13} it is adopted to make the double-clad PCF coupler. Two lengths of double-clad PCFs are first twisted, heated by a hydrogen flame with a flame size of approximately 10 mm, and then drawn gradually in the

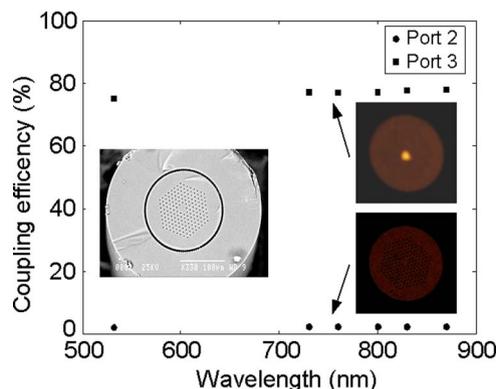


Fig. 1. (Color online) Coupling efficiency at output ports 2 and 3 of the double-clad PCF fiber coupler as a function of the illumination wavelength at input port 1. Left inset, a scanning electron microscopy image of a double-clad PCF. Right insets, digital camera photographs of output patterns of the double-clad PCF coupler at the wavelength 800 nm.

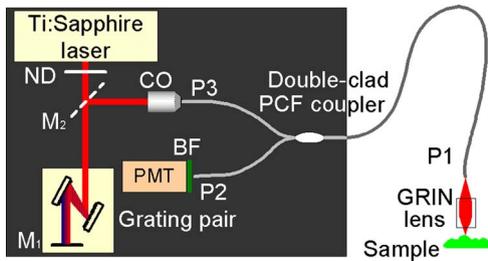


Fig. 2. (Color online) Schematic diagram of the nonlinear optical microscope with a three-port double-clad PCF coupler and a GRIN lens. Mirror M_2 (shown dashed) is located on a different plane from mirror M_1 . ND, neutral-density filter; BF, bandpass filter; CO, coupling objective.

fused region. Acrylate coating is removed only in the fused region. As the fibers are elongated and the fiber diameter is reduced, mode coupling occurs if the confined mode field in a PCF is extended to its neighboring double-clad PCF. Further, it is important to control the pulling length in the fused region, as it determines the splitting ratio of the coupler as well as the mode coupling condition in the core and clad regions. In the case of a short pulling length, where the rings of air holes in the two fibers are very close or partially collapsed, the multimode in the inner cladding is coupled to the neighboring fiber. Light propagated in the outer cladding will leak out quickly beyond the fused region, to where the acrylate coating still remains. In the fabrication system various coupling-starting pulling lengths¹¹ for the coupler are obtained, at which one arm of the coupler is terminated to form a 1×2 PCF coupler.

For a double-clad PCF coupler with a coupling-starting pulling length of approximately 6.1 mm, the coupling efficiency is measured from output ports 2 and 3 (see Fig. 2), while a laser beam in the wavelength range⁹ 532–870 nm is coupled to input port 1. As is shown in Fig. 1, the coupling efficiencies at ports 2 and 3 are approximately 2.2% and 77.5%, respectively, with a splitting ratio of 97/3 between ports 3 and 2 over the visible and near-infrared wavelength range. Under this condition the coupler reveals a low insertion loss of 1.1 dB between ports 1 and 3, while the insertion loss is as high as 16.6 dB between ports 1 and 2. The coupling efficiency of this coupler is different from that of a single-mode fiber coupler,^{7,9} which exhibits a lower coupling efficiency of port 3 in the visible wavelength region.

It has been shown in our previous study that a single-mode laser beam in the central core of the double-clad PCF makes a significant contribution to the excitation of nonlinear optical signals.⁵ Therefore it is essential to confirm the single-mode delivery feature of the double-clad PCF coupler. To this end, output patterns at ports 2 and 3 of the same coupler are recorded by a camera and are shown in the right-hand insets of Fig. 1 when port 1 is illuminated at the wavelength 800 nm. It can be seen that the arm (port 3) guiding the most power of the laser beam still maintains single-mode propagation in the central core, whereas only multimode propagation is observed from the other arm (port 2) in the near-infrared wavelength range. This result, together with

the splitting ratio shown in Fig. 1, implies that using port 3 for the delivery of the pulsed excitation beam and port 2 for the visible signal collection facilities the feature of efficient single-mode propagation in the core and multimode collection through the inner cladding. This unique feature, which cannot be obtained from a single-mode fiber coupler, may prove advantageous for compact all-fiber nonlinear optical microscopy.

It should be pointed out that a double-clad PCF coupler of the longer coupling-starting pulling length shows a higher splitting ratio of 74/26 between ports 3 and 2, resulting in multimode output patterns at both ports. This outcome might be due to the complete collapse of air holes surrounding the fiber core in the fused region. Optimization of the splitting ratio and the mode coupling of the PCF coupler is beyond the scope of this paper.

We construct an all-fiber nonlinear optical microscope based on the double-clad PCF coupler (shown in Fig. 1) and a GRIN lens, which is depicted in Fig. 2. A turnkey Ti:sapphire (Spectra Physics, Mai Tai) laser of wavelength range 730–870 nm provides short pulses with a pulse width of 80 fs and a repetition rate of 80 MHz. The laser beam is prechirped by double passing a pair of gratings (1200 grooves/mm, 28.7° blaze angle, Newport) before they are coupled to port 3 of the fiber coupler with a $4\times$, 0.12 NA coupling objective, CO. For a 1 m long double-clad PCF fiber, negative prechirping of approximately $-32,200 \text{ fs}^2$ is necessary to compensate for the group-velocity dispersion in the fused silica material. Such a dispersion compensation arrangement leads to an improvement of the nonlinear optical signal level by a factor of approximately 11 for a given average power ($<10 \text{ mW}$). The output laser beam at port 1 is focused through a 1 mm diameter, 0.2 pitch, 0.5 NA GRIN lens (GRINTECH) onto the sample. The excited nonlinear optical signals from the sample are collected via the detection arm (port 2) of the coupler attached to a PMT (photomultiplier tube). Therefore the double-clad PCF coupler acts as a beam splitter to separate the nonlinear optical signals from the excitation laser beam delivered by the fiber core.

To characterize the depth discrimination of the fiber optic nonlinear optical microscope, we measure the two-photon fluorescence axial response to a thin layer of AF-50 dye.^{5,9} Since the axial resolution and

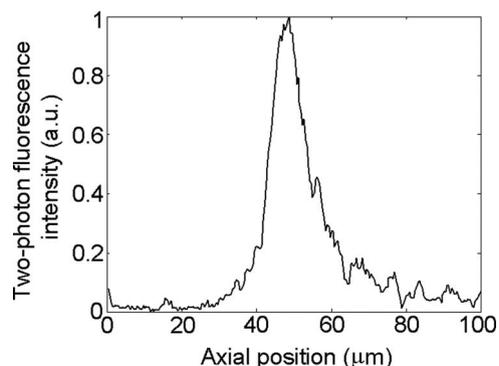


Fig. 3. Two-photon fluorescence axial response to a thin layer of AF-50 dye at an excitation wavelength of 800 nm.

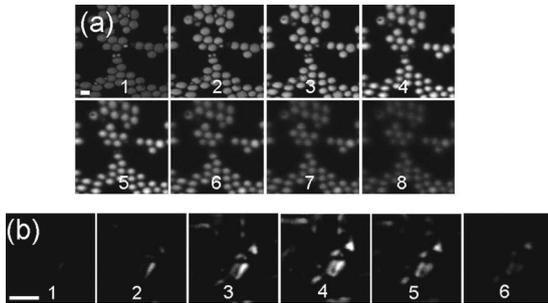


Fig. 4. Series of (a) two-photon fluorescence images of $10\ \mu\text{m}$ diameter fluorescent microspheres and (b) SHG images of KTP crystal powder. The excitation wavelength is $800\ \text{nm}$, and a $400/9\ \text{nm}$ bandpass filter is placed before the PMT when SHG images are acquired. Each set of images has an axial spacing of $5\ \mu\text{m}$ into the sample. The excitation power is approximately $10\ \text{mW}$ on the sample. Scale bars represent $10\ \mu\text{m}$.

the signal level of the system are dependent on the gap length between the fiber and the back surface of the GRIN lens, a gap length of approximately $8\ \text{mm}$ is chosen to optimize the signal level of the system. A typical two-photon fluorescence axial response to the thin layer is shown in Fig. 3, revealing the axial resolution of approximately $10\ \mu\text{m}$ in the nonlinear optical microscope. A slight improvement of axial resolution can be achieved when the back aperture of the GRIN lens is overfilled. However, that results in an approximately 25% degradation of the signal level of the system.

The optical sectioning ability of the new system is further demonstrated by sets of two-photon fluorescence images of $10\ \mu\text{m}$ diameter microspheres and SHG images of KTP crystal powder, which are displayed in Figs. 4(a) and 4(b), respectively. It can be seen that the system can collect high-resolution, three-dimensional images so that defects in the microspheres are well visualized. The results also imply that the miniature microscope could be used as a probe for the simultaneous detection of two-photon fluorescence and SHG signals in tumor tissue.

In summary, we have shown that a double-clad PCF coupler fabricated by the fused tapered method

can split the power of a laser beam as well as separate the near-infrared single-mode beam in the core from the visible multimode beam in the inner clad region. This unique feature of the double-clad PCF coupler facilitates all-fiber three-dimensional nonlinear optical microscopy with a GRIN lens, giving rise to the axial resolution of approximately $10\ \mu\text{m}$. Such an instrument will therefore be useful for a fiber optic nonlinear optical probe⁶ and side-pumped double-clad microstructure fiber lasers and amplifiers.¹⁴

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