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Mode-filtered large-core fiber for short-pulse delivery with reduced nonlinear effects

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Abstract

We present a large-core fiber (LCF) with a reduced nonlinear property for a single-mode beam delivery of intense ultrashort pulses. A tapered-fiber mode filter was fabricated in an LCF with the core diameter decreased from 20 μm to 6 μm at the tapered waist region surrounded by index-matched liquid. By the tapered geometry, the high-order mode was rejected so that our mode-filtered LCF acted as a single-mode fiber despite the multimode property of the original LCF. It has been found that this fiber class is suitable for applications, such as an endoscopic multiphoton microscope, that demand a flexible short-distance (<4 m) delivery medium of ultrashort pulses.

It is widely acknowledged that a conventional single-mode fiber (SMF) is vulnerable to nonlinear effects when transmitting intense short-pulse light due to its small core. Such a pulse can experience significant nonlinear processes that affect the propagation dynamics. As a consequence, the final duration of the pulse recompressed by the group-velocity dispersion (GVD) of the fiber may deviate from the transform-limited duration, making the resultant pulse less attractive for the application that demands an intense short pulse. The core size of an SMF is limited by the single-mode condition at an operation wavelength of λ . The normalized frequency, which is defined by $V = \pi d \text{NA} / \lambda$, must be below a certain value (2.405 for a step-index fiber), where d is the core diameter and NA is the numerical aperture, which is determined by the core-clad index contrast [1]. Increasing the core size by reducing the index contrast is hindered by the high bend loss of a low-NA SMF. On the other hand, an SMF of a large-mode area (LMA) can be accomplished by an extraordinary fiber geometry that suppresses the effective guidance of the high-order mode (HOM) as in LMA photonic crystal fiber (LMA-PCF) [2]. However, this type of fiber tends to be lossy under tight bends. LMA-PCF is not suitable for the applications where high degree of flexibility is required for the beam delivery media.

Multiphoton microscopy (MPM) based on a handheld head or a miniaturized endoscopic catheter demands an SMF of low nonlinearity for flexible beam delivery [3–5]. The single-mode requirement is not only for a fine spatial resolution but also relates with the efficiency of the multiphoton excitation. Under a multimode condition, a pulse splits to a plurality of modes that are dispersed in time by the different group velocities. One can still use a large-core multimode fiber with a careful light launch minimizing the HOM excitation. However,

sufficient suppression of HOM is difficult and needs additional means to filter out the residual HOM power. Fiber-optic mode filters have been introduced that facilitate the effective single-mode transmission by removing the HOM power from the fiber [6,7]. Helmchen et al. demonstrated that using a mode filter could enhance the two-photon excitation by better preserving the pulse quality [6], although the core diameter was only 10 μm , which was not as large as that of the typical LMA-PCF ($\sim 20 \mu\text{m}$). None has yet clarified how effectively HOM is rejected by a mode filter when it is used to make a large-core SMF.

In this Letter, we present an LMA fiber with a large core ($d = 20 \mu\text{m}$) for the MPM endoscopy that demands a flexible SMF. In our configuration, the HOM of a large-core fiber is rejected by a mode filter that is implemented in a large-core fiber (LCF). Our mode-filtered LCF (MF-LCF) acts as an SMF in spite of the multimode guidance of the original LCF. We found that the MF-LCF could suppress the HOM by a sufficient level required by the MPM application. We have carefully characterized the various performance factors at typical operation wavelengths of MPM systems: 0.8 μm and 1.0 μm . It has been found that the MF-LCF provides an attractive pulse delivery medium for its low nonlinearity, bending insensitivity, and compatibility with the conventional fibers.

A mode filter based on tapered fiber was fabricated from an LCF (20/390DC, Thorlabs Inc.) by using a commercial taper-fabrication station (LDS system, 3SAE Inc.) based on electric arc technology. Figure 1 shows the schematic of the tapered-fiber mode filter. The mode filter consists of three parts: first transition region with a length of L_t , waist region (L_w), and a second transition region (L'_t). Since the original core diameter of the LCF was 20 μm , multiple modes were supported by the core of $V = 5.17$ at 850 nm and $V = 4.23$ at 1.040 nm. At the waist region of the taper, the core diameter was estimated to be 6.2 μm within the single-mode condition as the clad diameter was reduced to 120 μm . There, the HOM propagated out of the core. This tapered section was covered by index-matching gel (G608N, Thorlabs Inc.) to get rid of the HOM power completely from the fiber. The nominal cutoff wavelength of the waist was 570 nm, and sufficiently far from the operation wave-lengths. The axial dimensions of each region were $L_t, L'_t = 7 \text{ mm}$ and $L_w = 7 \text{ mm}$, respectively. Note that successful HOM suppression may not be obtained for a marginally single-mode waist because of the leaky HOM guidance right below the mode cutoff [8].

The performance of our MF-LCF was tested with incoherent light sources at 850 nm and 1.040 nm, respectively. The mode-field intensity on the fiber output end surface was imaged by a digital camera with an objective lens, while the light was launched by an SMF to our MF-LCF in butt coupling. Two different conditions were given to the butt-coupled launch. In the first, a lateral offset of 10 μm was made between the fiber core axes (offset launch). In the second, no offset was given (centered launch). While keeping the same launching condition, mode-field patterns were imaged for the out-coming beams from our MF-LCF and a fiber section of LCF without a mode filter. Throughout the description of the experiment in the following, the out-coming beam of the LCF will be referred to the input of the MF-LCF, assuming the identical launch condition of the two cases.

Figure 2 shows a visual comparison between the mode-field patterns of the input and the output of the mode filter under the offset launch condition. Each image was normalized by the peak intensity. Confirmed by the characteristic patterns, the input of the MF-LCF was dominated by HOM: LP_{21} mode or LP_{11} mode in the linearly polarized mode designation [1]. In contrast, the output of the MF-LCF produced nearly Gaussian patterns which proved the sole existence of the LP_{01} mode.

A quantitative analysis on the HOM suppression was performed with the mode-field images acquired under different launch conditions. The intensity was plotted along the radial coordinate, r , by averaging azimuthally. Here, the radial intensity distributions were denoted by $R_c(r)$ for the centered launch and $R_o(r)$ for the offset launch. Figure 3 shows the radial intensity profiles measured at 1; 040 nm (upper row) and 850 nm (lower row), respectively. Each intensity plot was normalized by the intensity at the center ($r=0$). An exact determination of the HOM suppression could be performed with the data of Figs. 3(a) and 3(b) for $\lambda = 1; 040$ nm, where only LP_{01} and LP_{11} got effectively involved. Because of the zero amplitude of LP_{11} field at $r=0$, LP_{11} could not be efficiently excited by the centered launch, which suggests that R_c was composed of the LP_{01} field solely. On the other hand, $R_o(r=0)$, intensity of the offset launch at the center, was equal to the peak intensity of the LP_{01} component for the same reason. Therefore, $\Delta R(r) = R_o - R_c$ equals relative intensity distribution of the LP_{11} component that resided in R_o . This theoretical prediction was supported by the fact that ΔR matched to a squared Bessel function, $J_1^2(r)$ for the core region [1]. We estimated the HOM power suppression by taking the differential intensity ratio (DIR) that is defined by the ratio of ΔR of the input to that of the output. It was 20:8 dB at $\lambda = 1; 040$ nm by the ratio of the peaks.

This calculation method, however, does not make an exact estimation for $\lambda = 850$ nm where LP_{21} and LP_{02} modes were also involved. Then, R_c was composed of LP_{01} and LP_{02} mode power as R_c in Fig. 3(c) deviated from the typical pattern of LP_{01} intensity profile. Here, ΔR is lower than the HOM intensity. The DIR may underestimate the HOM suppression. However, it is still reasonable to take the DIR as a rough estimation of the HOM suppression, neglecting the contribution of LP_{02} . At $\lambda = 850$ nm, the DIR was 17:2 dB. After all, the residual HOM power was estimated to be only 1~2% of the inputted HOM power after the mode filter. In practice, an optimized launch to the fiber can further minimize the HOM excitation.

The insertion loss of our MF-LCF was measured as well. When single-mode light was launched by a large-core PCF (LMA-20, Thorlabs Inc.) in butt coupling to the MF-LCF, the output power of the MF-LCF was measured in respect to that of the PCF. The power ratio was 3:7 dB at 1; 040 nm and 2:2 dB at 850 nm. This loss includes the insertion loss of the MF-LCF and the coupling loss associated with the mode-field mismatch and the imperfect fiber cleaves. The net insertion loss of the MF-LCF was thought to be less than 1 or 2 dB for this reason.

The reduced nonlinear property of our MF-LCF was evaluated by experiment in this research. The area of a fiber core associated with nonlinear effects is conventionally estimated by the effective core area of A_{eff} , which is defined by the squared power divided by the spatial integration of squared intensity for the core mode [1]. Two different types of fiber were compared with our MF-LCF: SMF operating for 780–1; 000 nm (780HP, Thorlabs Inc.), and LMA-PCF for 600–1; 000 nm (LMA-20, Thorlabs Inc.). The core diameters were 5 μm for the SMF and 20 μm for the LMA-PCF, respectively. The core areas (A_{eff}) were 24:3 μm^2 , 204 μm^2 and 178 μm^2 at $\lambda = 850$ nm for the SMF, our MF-LCF and the LMA-PCF, respectively. And they were 28:5 μm^2 , 219 μm^2 and 172 μm^2 at $\lambda = 1; 040$ nm, respectively. The core area of our MF-LCF was ~8 times larger than that of the SMF. It was slightly larger ($\times 1:1$ or $\times 1:3$) than that of the commercial LMA-PCF.

The low nonlinear property of our MF-LCF was also verified by a pulse propagation experiment. Ultrashort pulses were transmitted through our MF-LCF (3.4 meters) and SMF (3.2 meters, 780HP, Thorlabs Inc.), respectively, to find the threshold power of nonlinear spectrum variation. The ultrashort pulse was generated by a mode-locked fiber laser running at a pulse rate of 76 MHz and a center wavelength of 1; 040 nm. The pulsed light was

launched to each fiber through a variable neutral density filter and a grating-pair compressor for prechirping. The shortest pulse duration could be made after getting a group delay of 60 fs/nm, which was calculated to be the GVD of ~1.5 m silica fiber at 1; 040 nm, neglecting the waveguide dispersion of the weakly guiding fibers. At the fiber output, the optical spectrum and average power of the outputted light were measured after stripping out the clad mode power. Figure 4 shows the change of pulse spectrum as a function of the average power for each fiber. Our laser generated a wide pulse spectrum with characteristic spikes at the spectral edges owing to the cavity characteristic of all-normal dispersion [9]. The transform-limited duration was calculated to be ~100 fs from the spectrum. As seen in Fig. 4(a), the pulse spectrum was changed from the small-power spectrum (at 0.1 mW) by a nonlinear-optic effect as the pulse power increased. A significant spectrum change occurred for the SMF when the average power increased above 7 mW. In contrast, as seen in Fig. 4(b), no significant nonlinear effect was observed for the MF-LCF below 52 mW, which is roughly the practical power limit of the sample irradiation for the MPM systems. This observation agreed well with the ratio of the effective core areas measured to be ~8 for those two fibers. The threshold power of significant nonlinear process was estimated to be higher than the maximum power of 52 mW for our MF-LCF, while a low average power of 10 mW was enough to make a large amount of nonlinear product in the conventional SMF as clear in Fig. 4(a).

We also tested the bending sensitivity of our fiber. We applied a one-turn bend to the MF-LCF with a curvature radius of 3 cm. No noticeable change of the intensity pattern was observed at the output. This verified that HOM re-excitation of mode coupling was negligible for the bending perturbation. The overall bend loss was so low that only 3% of the power was lost by the bend. On the contrary, we observed that the commercial LMA-PCF (LMA-20, Thorlabs Inc.) exhibited a high bend loss of >50% when the curvature radius of a one-turn bend was decreased below 3.3 cm at 1; 040 nm or 4.2 cm at 850 nm. We found a considerable bend loss even with a moderate curvature radius above 5 cm. This high bend sensitivity of the LMA-PCF may be unacceptable for MPM endoscopy because it limits the accessibility of the catheter to the internal site through a curved channel.

In conclusion, we have investigated various properties of the MF-LCF as a pulse delivery fiber of low nonlinear property. A large core was obtained with the MF-LCF in keeping the effectively single-mode characteristic by removing the HOM power. This feature of the large-core size and low nonlinearity was comparable or superior to the commercial LMA-PCF. The residual HOM power was found to be negligible even when the HOMs were dominant at the input. Furthermore, the low bend sensitivity makes our MF-LCF more practical for the targeted application of MPM endoscopy. This new class of LMA fiber can be a versatile alternative to the conventional media for flexible short-distance pulse delivery.

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Fig. 1.
(Color online) Schematic of the tapered-fiber mode filter that illustrates the HOM rejection.

Fig. 2.

(Color online) Mode-field images of the inputs and the outputs of the MF-LCF under the offset launch for the two different wavelengths, 850 nm and 1,040 nm, respectively.

Fig. 3. (Color online) Normalized radial intensity distributions of the input [(a) and (c)] and those of the output [(b) and (d)] of the MF-LCF. $\Delta R(r)$ was multiplied by 10 for better visibility in (b) and (d).

Fig. 4.

(Color online) Measured short-pulse spectra after being transmitted through the SMF (a) and our MF-LCF (b), respectively, displayed together with the mode-field images of the SMF, MF-LCF and the LMA-PCF acquired at $\lambda = 850$ nm (c).