

Low-loss propagation in Cr⁴⁺:YAG double-clad crystal fiber fabricated by sapphire tube assisted CDLHPG technique

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Abstract: Cr⁴⁺:YAG double-clad crystal fiber with an uniform 10-μm core was fabricated by using a sapphire tube as a heat capacitor to stabilize the power fluctuation of the CO₂ laser in the co-drawing laser-heated pedestal growth system. The uniformity of the fiber core showed a factor of 3 improvement compared to that without the use of sapphire tube. The variation of the core diameter is within the ±1.35-degree adiabatic criterion and has a autocorrelation length of 1.7 mm. The measured propagation loss is only 0.02 dB/cm. The sapphire tube also reduces the vertical temperature gradient during the crystal fiber growth process so the 10-μm crystal core exhibits a smooth perimeter. The sapphire tube assisted system can be applied to the growth of many other optical crystal materials.

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References and links

1. A. Sennaroglu, "Broadly tunable Cr⁴⁺-doped solid-state lasers in the near infrared and visible," *Prog. Quantum Electron.* **26**, 287-352 (2002).
2. Y. Kalisky, "Cr⁴⁺-doped crystals: their use as lasers and passive Q switches," *Prog. Quantum Electron.* **28**, 249-303 (2004).
3. M. M. Fejer, J. L. Nightingale, G. A. Magel, and R. L. Byer, "Laser-heated miniature pedestal growth apparatus for single-crystal optical fibers," *Rev. Sci. Instrum.* **55**, 1791-1796 (1984).
4. C. Y. Lo, K. Y. Huang, J. C. Chen, S. Y. Tu, and S. L. Huang, "Glass-clad Cr⁴⁺:YAG crystal fiber for the generation of superwideband amplified spontaneous emission," *Opt. Lett.* **29**, 439-441 (2004).
5. C. Y. Lo, K. Y. Huang, J. C. Chen, C. Y. Chuang, C. C. Lai, S. L. Huang, Y. S. Lin, and P. S. Yeh, "Double-clad Cr⁴⁺:YAG crystal fiber amplifier," *Opt. Lett.* **30**, 129-131 (2005).
6. L. Tong, R. R. Gattass, J. B. Ashcom, S. He, J. Lou, M. Shen, I. Maxwell, and E. Mazur, "Subwavelength-diameter silica wires for low-loss optical wave guiding," *Nature* **426**, 816-819 (2003).
7. Y. S. Lin, C. C. Lai, K. Y. Huang, J. C. Chen, C. Y. Lo, S. L. Huang, T. Y. Chang, J. Y. Ji, and P. Shen, "Nanostructures formation of double-clad Cr⁴⁺:YAG crystal fiber grown by co-drawing laser-heated pedestal," *J. Cryst. Growth* **289**, 515-519 (2006).
8. J. D. Love, W. M. Henry, W. J. Stewart, R. J. Black, S. Lacroix, and F. Gonthier, "Tapered single-mode fibres and devices," *IEE Proc. J. Optoelectron.* **138**, 343-354 (1991).
9. T. A. Birks and Y. W. Li, "The shape of fiber tapers," *J. Lightwave Technol.* **10**, 432-438 (1992).
10. D. Marcuse, "Mode conversion caused by surface imperfections of a dielectric slab waveguide," *Bell Syst. Tech. J.* **48**, 3187-3215 (1969).
11. C. T. Lee, M. L. Wu, L. G. Sheu, P. L. Fan, and J. M. Hsu, "Design and analysis of completely adiabatic tapered waveguides by conformal mapping," *J. Lightwave Technol.* **15**, 403-410 (1997).
12. D. Marcuse, *Theory of Dielectric Optical Waveguides* (Academic Press, 1991).
13. F. P. Payne and J. P. R. Lacey, "A theoretical analysis of scattering loss from planar optical waveguide," *Opt. Quantum Electron.* **26**, 977-986 (1994).
14. C. G. Poulton, C. Koos, M. Fujii, A. Pfrang, T. Schimmel, J. Leuthold, and W. Freude, "Radiation modes and roughness loss in high index-contrast waveguides," *IEEE J. Sel. Top. Quantum Electron.* **12**, 1306-1321 (2006).

15. C. W. Lan and C. Y. Tu, "Three-dimensional simulation of facet formation and the coupled heat flow and segregation in Bridgman growth of oxide crystals," *J. Cryst. Growth* **233**, 523-536 (2001).
16. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, "Optical coherence tomography," *Science* **254**, 1178-1181 (1991).

1. Introduction

Cr^{4+} :YAG crystal has been widely used as the gain medium for tunable solid-state lasers in the near infrared region and as the saturable absorber medium for passively Q-switched lasers due to its large pump absorption cross-section [1,2]. With its broad emission bandwidth from 1.2 to 1.6 μm that fall in the low loss window of silica fiber, Cr^{4+} :YAG crystal has the potential for the applications of fiber communications. Its broadband nature is resulted from the coupling of Cr^{4+} electronic states with the vibration states. For the applications of amplified spontaneous emission (ASE) light source and optical amplifier, the gain media in the fiber form is necessary for generating a larger gain by the better optical confinement of the waveguide structure together with a longer propagation length of the gain region. For the applications of lasers, the fiber structure of the gain media can also be superior to bulk crystal for reduced lasing threshold and better slope efficiency due to also the optical confinement effect and better heat dissipation. A well-known growth technique for crystal fibers is the laser-heated pedestal growth (LHPG) method [3]. A CO_2 laser is used as the heating source to melt the source rod where the crystal fiber is drawn from. It is crucible-free and can, therefore, produce high-purity, low-defect-density single crystal fibers. The fiber diameter was difficult to be reduced to below 30 μm that was limited by the a few tens of microns focal spot size of the laser used in the LHPG system. Fibers with a smaller core diameter are desired for high optical intensity. To further reduce the core size, a co-drawing LHPG (CDLHPG) technique was developed [4,5]. Single crystal fiber of 68- μm diameter is inserted into a fused-silica capillary to form the cladding layer. A double-clad crystal fiber (DCF) structure is formed with the formation of an inner cladding layer made of fused silica and YAG mixture. The fiber core diameter is reduced during the formation of the inner cladding layer, and can be as small as 10 μm . However, the fiber core diameter is very non-uniform because the core size is very sensitive to the power stability of the heating laser ($< 0.5\%$ power fluctuation in our case) during the growth process, especially when the core diameter is small. As a result, the 10- μm -core fiber has about 60% core variation typically.

Tong, *et al.*, successfully fabricated silica wires with diameters down to several tens of nanometers by using an indirect heating mechanism through the tip of a tapered sapphire tip in their fiber drawing system [6]. To improve the core uniformity of small-core crystal fiber, we propose, for the first time, to use the thermal capacitance effect in a similar way to suppress the power fluctuation of heating laser by incorporating a sapphire tube in the CDLHPG system. The variation of the 10- μm core Cr^{4+} :YAG DCFs were improved with a factor of 3 from 58% to 17%. The propagation loss of the 10- μm -core fiber grown by this method is as low as 0.02 dB/cm. Since the length of heating zone was 2.5 times longer with the use of sapphire tube assisted growth, the temperature gradient along the growth direction is reduced significantly. The crystal fiber core exhibits a distinct shape by this growth method. The interesting core shapes of the Cr^{4+} :YAG DCFs with several core diameters are presented.

A few hundred microwatts of ASE was obtained by a 10- μm -core and 6.4-cm-long Cr^{4+} :YAG DCF. Such broadband light source with a 3-dB bandwidth of 265 nm is useful for optical fiber communications as well as optical coherence tomography. This technique can also be applied to the growth of other materials for better uniformity.

2. Sapphire tube assisted CDLHPG fiber growth process

The source rods for crystal fiber growth were commercially available 0.5-mol.-%-doped Cr^{4+} :YAG with [111] orientation. The absorption coefficient was approximately 4.5 cm^{-1} at 1064 nm. After two diameter-reduction steps, the crystal fiber with 68- μm core diameter was

inserted into a fused silica capillary tube with 76- and 320- μm inner and outer diameters. The filled capillary was then co-drawn by the sapphire tube assisted LHPG system at a growth speed of 3 mm/min. The schematic of the sapphire tube assisted CDLHPG growth system is shown in Fig. 1. The length of the sapphire tube was 1.5 mm, and the outer and inner diameters were 1200 μm and 480 μm , respectively. The capillary was inserted into the sapphire tube for DCF growth. A donut-shape CO_2 laser beam was focused and shone around the outer wall of the sapphire tube, to heat and generate a strong thermal radiation for melting the filled silica capillary. The power fluctuation of the CO_2 laser was kept within 0.5%. The sapphire tube serves as a thermal capacitor to minimize the thermal variation due to the power fluctuation of the CO_2 laser. The 1970 $^\circ\text{C}$ melting temperature of the YAG is comparable to the 1600 $^\circ\text{C}$ soften temperature of the fused silica. The heating causes a strong inter-diffusion between the YAG core and fused-silica capillary, and an additional inner cladding layer made of the mixture was formed [5,7]. Not only the crystal fiber is cladded but also the fiber core is reduced with the formation of the inner cladding layer. A negative pressure of 200 torrs prevented the generation of bubbles inside the waveguide during the growth process. In this way, Cr^{4+} :YAG DCFs with 10- μm core were successfully fabricated.

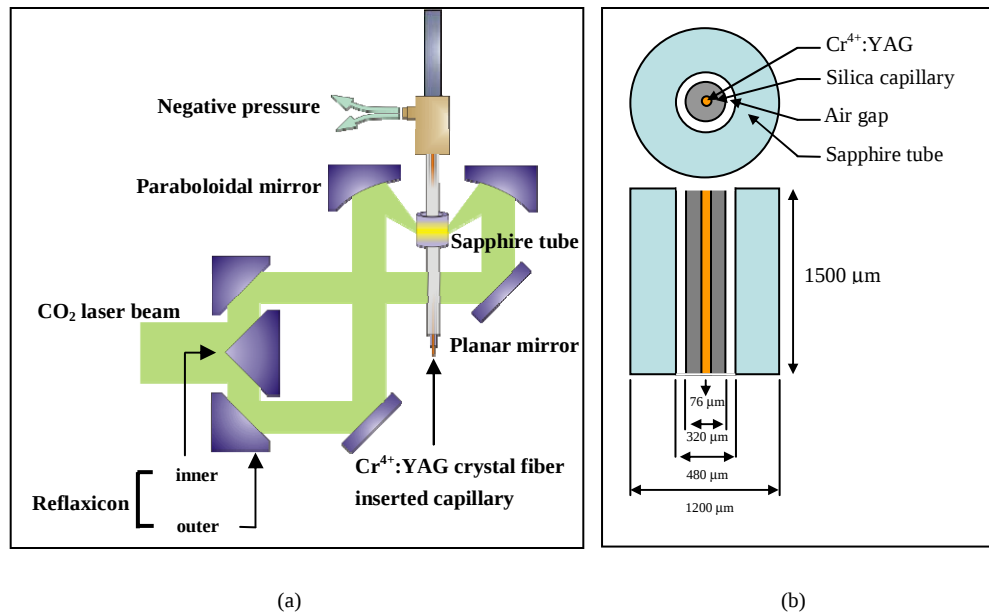


Fig. 1. (a). The schematic of sapphire tube assisted CDLHPG system. (b) The end view and side view of the sapphire tube with fused-silica capillary.

3. Results and discussions

3.1 Core uniformity and propagation loss

The core diameter was measured by a LabVIEW vision program along a 50-mm length. The resolutions are both 0.5 μm along and transverse to the fiber axis. Variation of the core diameter was defined as the peak-to-peak difference divided by the averaged value. The core diameter variations of these samples are shown in Fig. 2. For the case of the 10- μm core, the core variation was reduced from 58% to 17% by using the sapphire tube in the growth system. It is more than a factor of 3 improvement. From the reduced core variation, the thermal capacitance effect of the sapphire tube to alleviate the fluctuation of CO_2 laser power was confirmed.

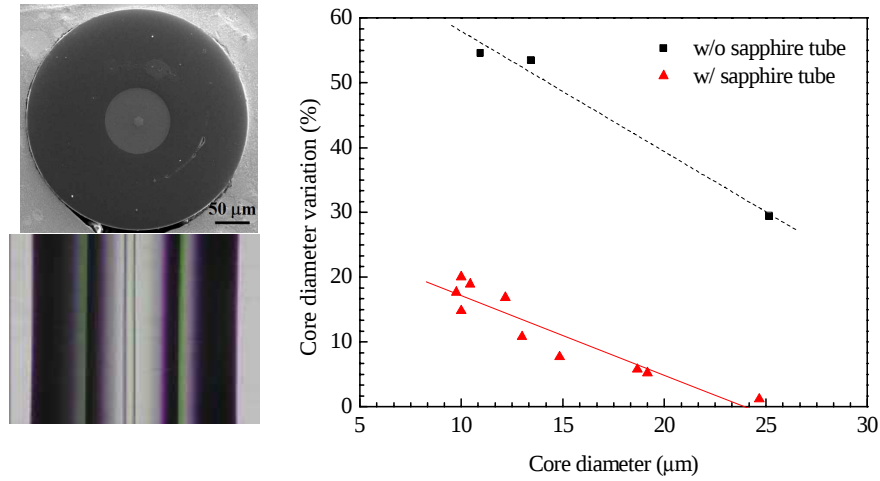


Fig. 2. The left images are the end view and side view of a 10-μm-core Cr⁴⁺:YAG DCF. Core diameter variation for fibers fabricated with and without the use of sapphire tube.

The variation of core diameter may lead to a loss of propagating power because of the coupling of a low-order mode to a high-order mode. The tapered angle Ω derived from the core variation should meet the adiabatic criterion as follows [8,9]:

$$\Omega \leq \frac{\rho(\beta_1 - \beta_2)}{2\pi}. \quad (1)$$

where ρ is the core radius, β_1 and β_2 are the respective propagation constants of the modes before and after the tapering. For the 10-μm-core fiber, the adiabatic criterion requires that the tapering angle of the core must be within ± 1.35 -degree to avoid the mode leakage. As shown in Fig. 3, the core diameter profile along the propagation axis was measured by the LabVIEW vision program. The spacing between each sampling points of the side view image was 100 μm. The tapering angle was determined by the slope. All the measured core tapering angles of the fiber grown with the use of sapphire tube meet the ± 1.35 -degree requirement.

Without mode leakage, the scattering loss from the random fluctuation of core diameter may become the dominant light attenuation source [10-14]. The autocorrelation length of the core diameter variation as a function of position was found to be 1.7 mm, as shown in Fig. 4. It is 2 orders of magnitude longer than the core diameter, and thus alleviates the scattering loss. Such a long length is expectable since the core variation due to the heating fluctuation power becomes slower, with the aid of the sapphire tube as a heat capacitor. The measured fiber propagation losses with several fiber core diameters are shown in Fig. 5. One dot means one propagation loss measurement of the Cr⁴⁺:YAG DCF. The fiber losses range from 0.02 to 0.08 dB/cm. Compared with those of the fiber grown without the use of sapphire tube, the propagation loss was improved from 0.6 dB/cm to 0.02 dB/cm for a 10-μm-core fiber.

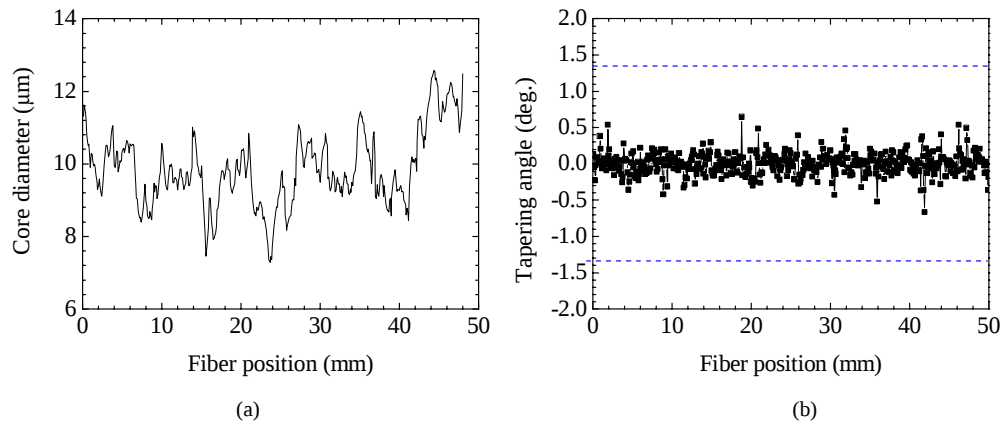


Fig. 3. (a). The core diameter profile in the propagation axis. (b) Tapering angles of the fiber fabricated with the use of sapphire tube during LHPG growth meet the 1.35-degree adiabatic criterion.

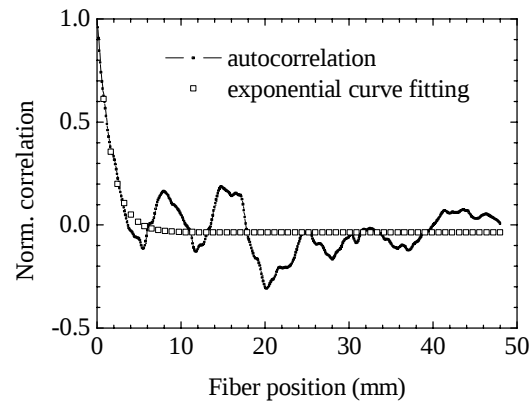


Fig. 4. The autocorrelation curve of the core diameter for a 10-μm-core DCF.

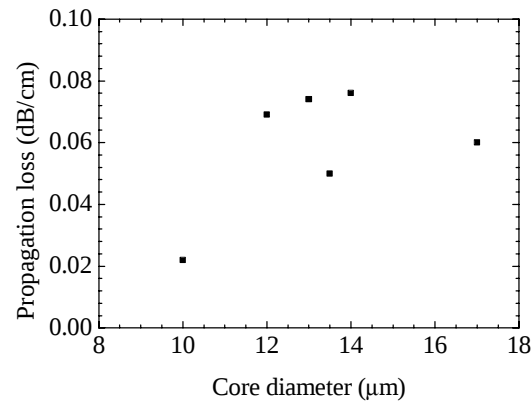


Fig. 5. The propagation losses of the Cr⁴⁺:YAG DCFs with various core diameters.

3.2 Comparison of the end faces without and with the use of sapphire tube assisted growths

In addition to the heat power stabilization with its thermal capacitance effect, the sapphire tube also provides a longer heating zone with a reduced vertical temperature gradient. The scanning electron microscope (SEM) images of the core end faces of the Cr^{4+} :YAG DCF using growth methods without and with the use of sapphire tube are shown in Figs. 6 and 7. As shown in Fig. 6, the core shape changed as the core diameter reduced. The core shapes of 17-, 15-, and 10- μm -core fibers are circular, dodecagonal, and hexagonal in sequence. It was because of the constitutional melt supercooling at the growth interface [15]. Due to the high temperature gradient, the interfacial kinetic effects near the solid-melt interface become prominent. Without supercooling, the flow and thermal fields, as well as dopant fields at the interface are axisymmetric. With a few degrees of supercooling, the interface is no longer at the melting point, and the lowest temperature occurs inside the facets. When the core diameter grew smaller, the higher temperature led the lower viscosity of surrounding melt and higher extension rate of crystal core to enhance the $\{110\}$ and $\{112\}$ facets. With large temperature gradient along YAG $[111]$ axis, the dendrite forms due to the strong competition between $\{110\}$ and $\{112\}$ faces. Fibers grown by the sapphire tube assisted method showed smoother interfaces between the core and the inner clad. Comparing Figs. 6 and 7, the cores show similar circular, dodecagonal and hexagonal shapes, but the cores grown with the use of sapphire tube are 6 μm smaller than those grown without the use of sapphire tube when having similar shapes. The hot zone lengths that with and without the use of sapphire tube assisted growth were around 1000 μm and 400 μm , respectively. The temperature gradient of the sapphire tube assisted growth was 2.5 times smaller so the growths in $\{110\}$ and $\{112\}$ facets were delayed. The circular shape should be more favorable than the dodecagonal and hexagonal shapes for coupling with SMFs.

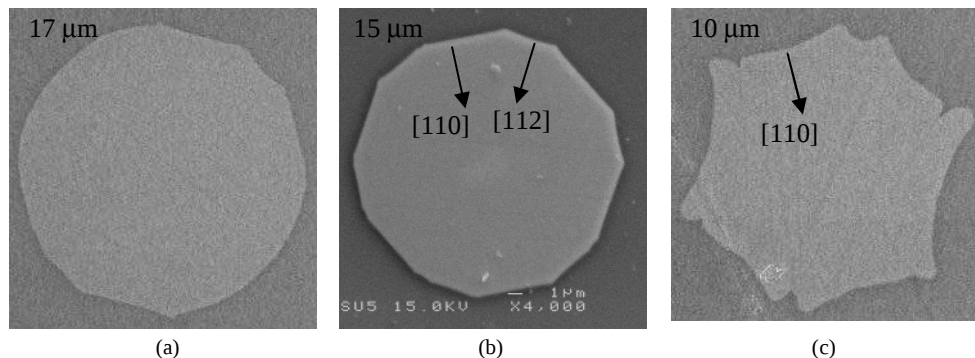


Fig. 6. Cr^{4+} :YAG DCF cores of (a) 17- μm , (b) 15- μm , and (c) 10- μm diameters without the use of sapphire tube.

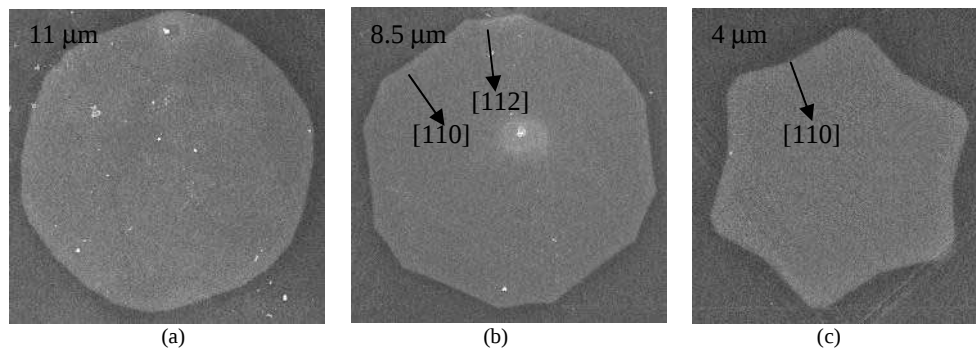


Fig. 7. Cr^{4+} :YAG DCF cores of (a) 11- μm , (b) 8.5- μm , and (c) 4- μm diameters with the use of sapphire tube.

3.3 ASE generation

A Cr^{4+} :YAG DCF with 10- μm core diameter and 6.4-cm fiber length was used to generate ASE. The Cr^{4+} :YAG DCF was packaged using Pb-Sn alloy for heat dissipation. A 1064-nm Yb-fiber laser was used as the pump source. Figure 8 shows the measured ASE power as a function of the absorbed pump power. This ASE light source is useful as a light source for fiber communications or optical coherence tomography (OCT) [16]. The estimated axial resolution using the Cr^{4+} :YAG DCF ASE light source for OCT is 3.6 μm in free space.

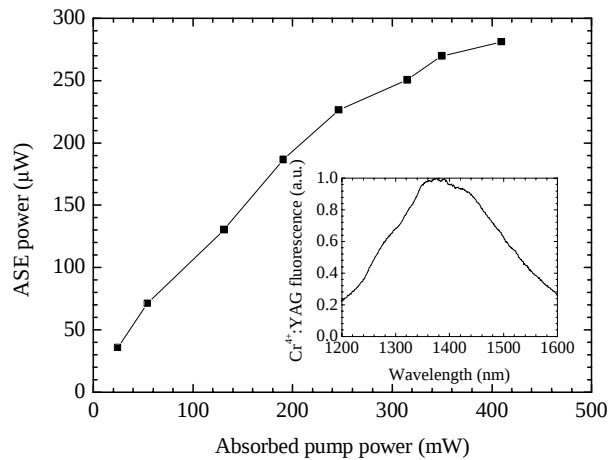


Fig. 8. The ASE power measurement of 10- μm -core Cr^{4+} :YAG DCF. The inset shows the ASE spectrum with 265-nm bandwidth.

3.4 Coupling efficiency with SMF28

The refractive index profile of the Cr^{4+} :YAG DCF was obtained by measuring the Fresnel reflection of the end face by laser scanning confocal microscopy with a 635-nm distributed feed-back laser. The 1.46 refractive index of the fused silica outer clad was used as the reference. As shown in Fig. 9, the measured refractive indices of the core, inner clad, and outer clad were 1.82, 1.66, and 1.46, respectively. The fiber is multimode since the refractive index difference between core and inner-clad is quite large. The mode coupling efficiency of the DCF fundamental mode to single mode fiber was simulated at 1064-nm pump wavelength, 1400-nm emission center wavelength, and 1550-nm communication wavelength, respectively. A circular core shape of DCF was assumed to simplify the simulation model. The simulation results are shown in Fig. 10(a), the core diameters for optimum mode coupling efficiency at 1064 nm, 1400 nm, and 1550 nm are 11.5 μm , 13.5 μm , and 14.5 μm core diameters, respectively. All the optimum mode coupling efficiencies exceed 96%. Based on the simulation result, a 13-cm-long fiber in 13.5- μm core was chosen to measure the insertion loss from a single mode fiber to DCF and to another single mode fiber by butt coupling scheme. As shown in Fig. 10(b), the insertion loss was measured from 1260 nm to 1640 nm by using a tunable laser as the light source. The insertion loss varies from 1.97 dB to 2.88 dB. When compared with the simulation, it is clear that the insertion loss is mainly from Fresnel losses at the uncoated end faces.

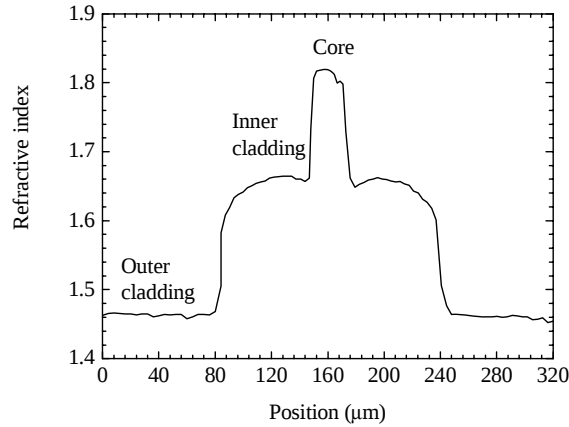


Fig. 9. The refractive index profile of a 320- μm -diameter Cr^{4+} :YAG DCF.

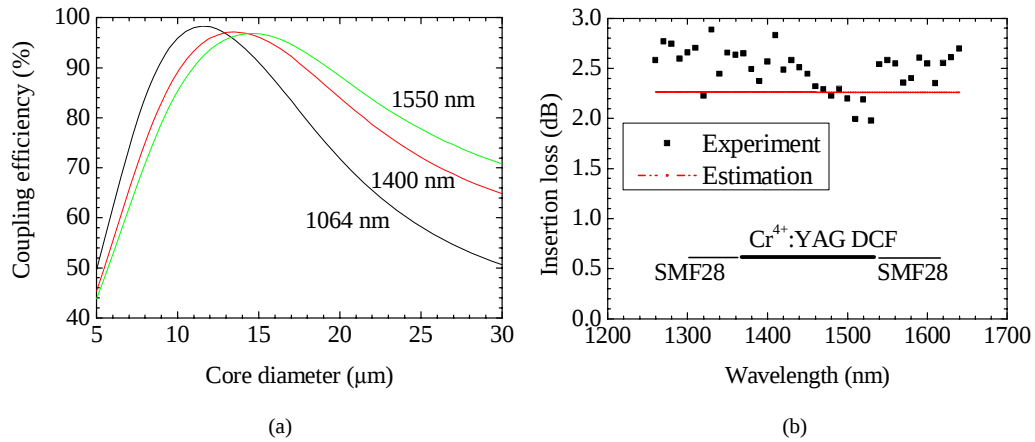


Fig. 10. (a). The simulation results of mode coupling efficiencies between the SMF28 and the Cr^{4+} :YAG DCF using different signal wavelengths. (b) The measured and simulated insertion losses. The inset shows the measurement scheme.

4. Conclusion

The sapphire tube assisted CDLHPG technique successfully suppressed the heating fluctuation from the CO_2 laser power instability during the fiber growth process. A factor of 3 improvement of the core variation of the 10- μm -core Cr^{4+} :YAG DCF was demonstrated. The tapering angles along the 10- μm -core fiber are all within the ± 1.35 -degree adiabatic criterion. The 1.7-mm autocorrelation length was long enough so the variation of the core has reduced influence on the fiber propagation loss. The propagation loss was improved from 0.6 dB/cm to 0.02 dB/cm for 10- μm -core fibers. The variation of the crystal fiber core can be further improved by optimizing the sapphire tube dimensions. The core shapes with the use of sapphire tube assisted growth were smoother due to the slow temperature gradient. For the sapphire tube assisted growth, the temperature gradient of the melting zone was 2.5 times smaller than without the use of sapphire tube assisted growth, that suppress the generation of {110} and {112} crystalline facets. The circular core shape of the 10- μm -core crystal fiber is favorable for coupling to single mode fibers. Hundred microwatts of ASE power were obtained by a 10- μm -core and 6.4-cm-length fiber with a 3-dB emission bandwidth of 265 nm. The light source can be used to achieve a 3.6- μm axial resolution for OCT system.