

# Broadband emission from Cr-doped fibers fabricated by drawing tower

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**Abstract:** We report on the first fabrication of a Cr-doped fiber using a drawing-tower method with Cr:YAG as the core of the preform. Both Cr<sup>3+</sup> and Cr<sup>4+</sup> ions coexist in the Cr-doped fiber, and the amplified spontaneous emission (ASE) spectrum shows a broadband emission of 1.2 to 1.55  $\mu\text{m}$  which can not be realized by using currently available fiber amplifiers. This indicates that the new Cr-doped fibers have the potential for being used as a broadband fiber amplifier to cover the bandwidth of the entire 1.3-1.6  $\mu\text{m}$  range which exhibit 300 nm usable spectral bands.

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## References and links

1. T. Kasamatsy, Y. Yano, and H. Seller, "1.50- $\mu\text{m}$ -band gain-shifted thulium-doped fiber amplifier with 1.05- and 1.56- $\mu\text{m}$  dual-wavelength pumping," *Opt. Lett.* **24**, 1684-1686 (1999).
  2. Y. Ohishi, T. Kanamori, T. Kitagawa, S. Takahashi, E. Snitzer, and G.H. Sigé, Jr., "Pr<sup>3+</sup>-doped fluoride fiber amplifier operating at 1.31  $\mu\text{m}$ ," *Opt. Lett.* **16**, 1747-1749 (1991).
  3. M. V. Iverson, J. C. Windscheif, and W. A. Sibley, "Optical parameters for the MgO:Ni<sup>2+</sup> laser system," *Appl. Phys. Lett.* **36**, 183-184 (1980).
  4. T. Suzuki and Y. Ohishi, "Broadband 1400 nm emission from Ni<sup>2+</sup> in zinc—alumino—silicate glass," *Appl. Phys. Lett.* **84**, 3804-3806 (2004).
  5. S. Tanabe and X. Feng, "Temperature variation of near-infrared emission from Cr<sup>4+</sup> in aluminate glass for broadband telecommunication," *Appl. Phys. Lett.* **77**, 818-820 (2000).
  6. C. Batchelor, W. J. Chung, S. Shen, and A. Jha, "Enhanced room-temperature emission in Cr<sup>4+</sup> ions containing alumino-silicate glasses," *Appl. Phys. Lett.* **82**, 4035-4037 (2003).
  7. 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 Cr<sup>4+</sup>:YAG crystal fiber amplifier," *Opt. Lett.* **30**, 129-131 (2005).
  8. C. Y. Lo, K. Y. Huang, J. C. Chen, S. Y. Tu, and S. L. Huang, "Glass-clad Cr<sup>4+</sup> YAG crystal fiber for the generation of superwideband amplified spontaneous emission," *Opt. Lett.* **29**, 439-441 (2004).
  9. J. C. Chen, C. Y. Lo, K. Y. Huang, F. J. Kao, S. Y. Tu, and S. L. Huang, "Fluorescence mapping of oxidation state of Cr ions in YAG crystal fibers," *J. Cryst. Growth* **274**, 522-529 (2005).
  10. E. Snitzer and R. Tummineli, "SiO<sub>2</sub>-clad fibers with selectively volatilized soft-glass cores," *Opt. Lett.* **14**, 757-759 (1989).
  11. Cr:YAG crystal rod, Fujian JDSU CASIX Inc., Fujian, China (2005).
  12. T. Murata, M. Torisaka, H. Takebe, and K. Morinaga, "Compositional dependence of the valency state of Cr ions in oxide glasses," *J. Non-Cryst. Solids* **220**, 139-146 (1997).
  13. Y. G. Choi, K. H. Kim, Y. S. Han, and J. Heo, "Oxidation state and local coordination of chromium dopant in soda-lime-silicate and calcium-aluminate glasses," *Chem. Phys. Lett.* **329**, 370-376 (2000).
  14. U. Hömmerich, H. Eilers, W. M. Yen, J. S. Hayden, and M. K. Aston, "Near infrared emission at 1.35  $\mu\text{m}$  in Cr doped glass," *J. Lumin.* **60** and **61**, 119-122 (1994).
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## 1. Introduction

The breakthrough technology in dry fiber fabrication has opened the possibility for using fiber bandwidths all the way from 1.3 to 1.6  $\mu\text{m}$ . The usable spectral band for the number of channels in a wavelength division multiplexing (WDM) system strongly depends on the gain bandwidth of the fiber amplifiers. For example, the well-known erbium (Er)-doped fiber amplifier provides gain in the C band (1530-1565 nm), in the L band (1570-1605 nm), and even in the S band (1450-1520 nm) which totaled 140 nm usable spectral bands. The other types of fiber amplifiers such as thulium (Tm)-doped [1], produced gains in the S band (1450-1520 nm) and praseodymium (Pr)-doped [2] operated gains in the O band (1260-1360 nm). However, the gain bandwidths of the Er-doped, Tm-doped, and Pr-doped fiber amplifiers cannot fully cover the whole 1.3-1.6  $\mu\text{m}$  range with a single fiber amplifier. Therefore, it may be interesting to develop a single fiber amplifier which can operate the wide bandwidth of the 1.3-1.6  $\mu\text{m}$  emission.

The transition-metal-doped materials such as  $\text{Ni}^{2+}$  ions [3-4] and  $\text{Cr}^{4+}$  ions [5-6] have shown broadband 1.3-1.6  $\mu\text{m}$  emissions. Recently, a  $\text{Cr}^{4+}$ :YAG crystal fiber amplifier has been demonstrated by the use of a codrawing laser-heated pedestal growth (LHPG) method [7-9]. Up to 10 dB of gross gain at a wavelength of 1.52  $\mu\text{m}$  was achieved at a pump power of 0.83 W [7]. The  $\text{Cr}^{4+}$ -doped fiber amplifier can be employed in the whole 1.3-1.6  $\mu\text{m}$  range. However, it is difficult to fabricate a core diameter less than 10  $\mu\text{m}$  by following the LHPG method. Furthermore, the growth of the  $\text{Cr}^{4+}$ -doped fibers is slow (about 10 mm/min) and the uniformity of the core diameter varies in lengths. Therefore, it may be difficult to integrate the LHPG fabricated  $\text{Cr}^{4+}$ -doped fibers with the standard single-mode fibers for lightwave system applications.

In this paper, we propose and fabricate a Cr-doped fiber by employing a commercial drawing-tower method which has a better core diameter uniformity for adiabatic transmission. Since the core size is about the same as that of a standard single-mode fiber, a low-loss fusion splice can readily be done. The major benefit of the Cr-doped fiber is a broadband emission from 1.2 to 1.55  $\mu\text{m}$  which has not been realized by using currently available fiber amplifiers. This broadband Cr-doped fiber may be used as a new fiber amplifier to cover the fiber bandwidths in the whole low-loss window of a silica fiber to further increase the transmission capacity of the WDM system for lightwave communication applications.

## 2. Fabrication

The  $\text{Cr}^{4+}$ -doped YAG preform was fabricated using a rod-in-tube (RIT) method [10]. A silica rod had a hole first drilled in the center of one end and tapered the other end to form a cone shape. Then the sample was inserted with a  $\text{Cr}^{4+}$ -doped YAG crystal rod [11] to constitute the preform. The silica rod became the cladding when the assembled preform was drawn into fiber by using the drawing-tower method. Figure 1(a) shows a schematic diagram of a  $\text{Cr}^{4+}$ -doped YAG preform. The diameter and the length of the  $\text{Cr}^{4+}$ -doped YAG crystal were 5 mm and 5 cm, respectively. The diameter of the preform was 62.5 mm in order for the ratio of the core to the cladding diameter to become 10/125 after the fiber drawing. A photo image of the fabricated  $\text{Cr}^{4+}$ -doped YAG preform is shown in Fig. 1(b).

A commercial drawing tower with a 28-m height and a carbon-resistant furnace was used to fabricate the Cr-doped fibers. The material properties of  $\text{Cr}^{4+}$ :YAG and  $\text{SiO}_2$  used in this study are listed in Table I. Due to the different thermal expansion coefficients between the  $\text{Cr}^{4+}$ -doped YAG crystal and the silica, as indicated in Table I, the heating temperature was kept gradual and slow proceeded. The preform was loaded into the center of the furnace first, and then the temperature was augmented from 1100  $^\circ\text{C}$  to 2150  $^\circ\text{C}$  with a ramp rate of 20

$^{\circ}\text{C}/\text{min}$ . The drawing temperature was set at  $2050^{\circ}\text{C}$  when the first lump of perform was dropped. The drawing temperature was much higher than the melting point  $1970^{\circ}\text{C}$  of Cr:YAG and the softening point  $1670^{\circ}\text{C}$  of silica, as indicated in Table I. The drawing speed was set at  $200\text{ m}/\text{min}$  that was much lower than the speed of  $1.5\text{ km}/\text{min}$  in drawing a conventional single-mode fiber.

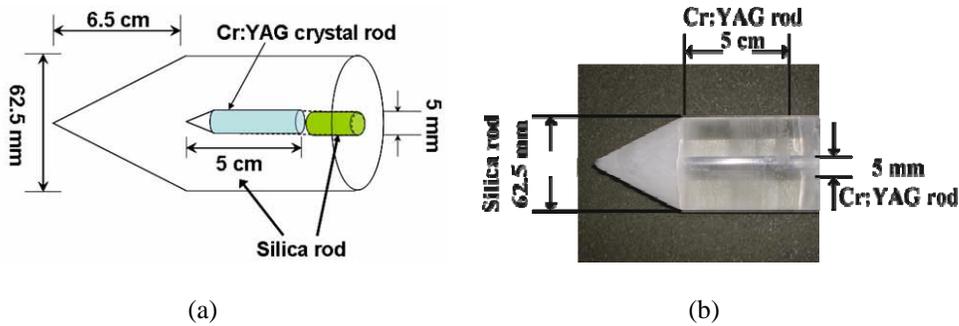


Fig. 1. (a) A schematic diagram of a  $\text{Cr}^{4+}$ -doped YAG preform and (b) a photo of a fabricated  $\text{Cr}^{4+}$ -doped YAG preform.

Table 1. The material properties of  $\text{Cr}^{4+}$ :YAG and  $\text{SiO}_2$ .

	$\text{Cr}^{4+}$ :YAG	$\text{SiO}_2$
Annealing point ( $^{\circ}\text{C}$ )	N.A.	1140
Softening point ( $^{\circ}\text{C}$ )	N.A.	1670
Melting point ( $^{\circ}\text{C}$ )	1970	N.A.
CTE ( $10^{-7}/^{\circ}\text{C}$ )	77 ~ 82	5.5
Index	1.82	1.458

### 3. Measurements and results

Ten kilometers of the Cr-doped fibers have successfully been drawn. Figure 2(a) shows a fiber end face with a  $9\text{-}\mu\text{m}$ -diameter core and a  $125\text{-}\mu\text{m}$ -diameter cladding. Smaller core diameters of the Cr-doped fibers could also be obtained by using different diameters of the silica rod. The refractive index profile was measured with a conventional instrument, EXFO 9200. Figure 2(b) shows a refractive-index profile with  $n_{\text{core}} = 1.5$  and an index difference  $\Delta = 2.93\%$ . The refractive index exhibited a step around 1.48 because of the inter-diffusion between YAG and  $\text{SiO}_2$ .

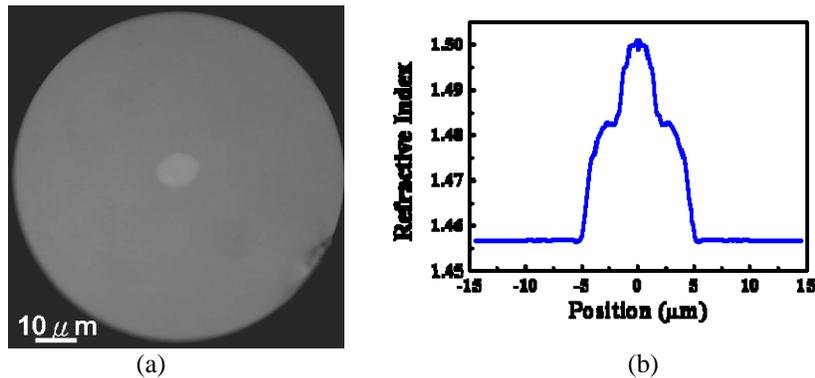


Fig. 2. (a) Photograph of the cleaved end with a  $9\text{-}\mu\text{m}$ -diameter core and (b) the refractive index profile of the Cr-doped fiber.

It is well known that Cr ions have several oxidation states such as  $\text{Cr}^{2+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Cr}^{4+}$ ,  $\text{Cr}^{5+}$ , and  $\text{Cr}^{6+}$ . Cr ions are likely to exist in the stable form of +3 oxidation state and are hardly found in tetravalent coordination state in normal glasses. The stable +4 oxidation state of Cr ions has been found in aluminate, alumino-silicate, and gallate glasses, which results in the absorption spectrum at ranges of 600-1000 nm [12]. Therefore, to measure the fluorescence spectrum of Cr-doped fibers, the Ti-sapphire laser with a wavelength of 700-1000 nm was used as the light source. In Fig. 3(a), the fluorescence spectrum of the Cr-doped fiber was excited by 800-nm in wavelength with an initial power of 200 mW. The emission peak was at 1  $\mu\text{m}$ , which is similar to the typical  $\text{Cr}^{3+}$  fluorescence spectrum in  $\text{SiO}_2$  glass [13]. The shoulder was extended to 1.6  $\mu\text{m}$ , which should be attributed to the  $\text{Cr}^{4+}$  ions [13-14]. Both  $\text{Cr}^{3+}$  and  $\text{Cr}^{4+}$  ions coexist in Cr-doped fibers and the  $\text{Cr}^{3+}$  ion is dominant. Further evidence can be shown in Figs. 3(b) and 3(c) where the amplified spontaneous emission (ASE) spectra of the Cr-doped fiber are through 6.1-cm and 8.3-cm propagation lengths, respectively. In Fig. 3(b), the central wavelength of the ASE spectrum was 1.15  $\mu\text{m}$ . In contrast to Fig. 3(b), the central wavelength of the ASE spectrum was shifted to a longer wavelength at 1.32  $\mu\text{m}$ , as shown in Fig. 3(c). This is due to the re-absorption of  $\text{Cr}^{3+}$  fluorescence which causes the re-emission of  $\text{Cr}^{4+}$  ions to become apparent when the pumping light travels through a longer length of the Cr-doped fiber. The dip of the ASE spectrum at the wavelength of 1.4  $\mu\text{m}$  in Fig. 3(c) was the absorption of  $\text{OH}^-$  ions which was caused by the cooling process when the preform was drilling. Therefore, an improvement in the fabrication of the Cr-doped fibers to reduce the  $\text{OH}^-$  ions is necessary.

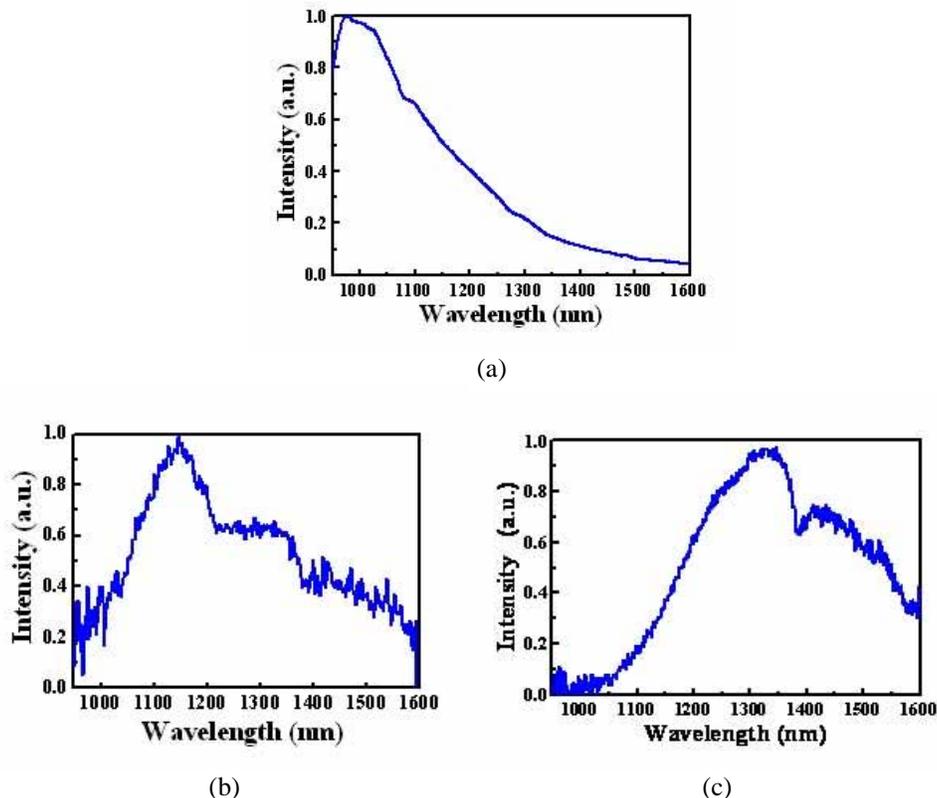


Fig. 3. (a) The fluorescence spectrum of the Cr-doped fibers, and the ASE spectra of the Cr-doped fibers through (b) 6.1-cm length and (c) 8.3-cm length.

Figure 4 shows the far-field pattern of a Cr-doped fiber. A 5-cm-length Cr-doped fiber was spliced with a single-mode fiber for the measurement of the far-field pattern. The divergent angle of the Cr-doped fiber was  $17^\circ \times 15^\circ$  and similar to a single mode fiber of  $16^\circ \times 16^\circ$ . This indicates that the Cr-doped fiber was good for splicing with a standard single-mode fiber. Figure 5 shows the transmission loss of the Cr-doped fibers including absorption and propagation loss. The measured transmission loss was 0.2dB/cm and 1dB/cm at the wavelengths of 1.55  $\mu\text{m}$  and 1.3  $\mu\text{m}$ , respectively. The dominant loss in transmission of the Cr-doped fiber was absorption.

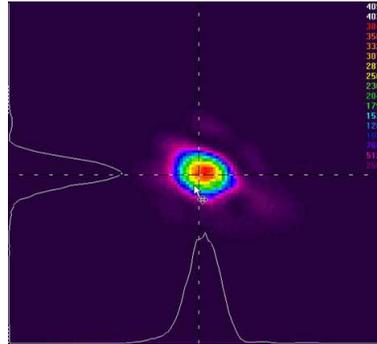


Fig. 4. The far-field pattern of the Cr-doped fiber.

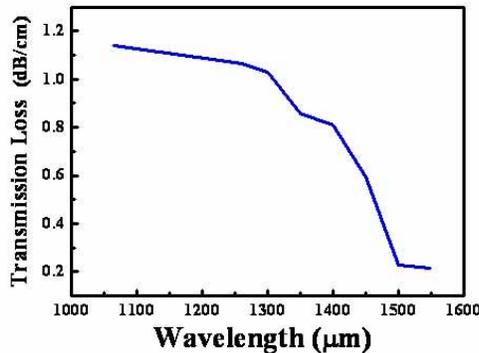


Fig. 5. The transmission loss of the Cr-doped fiber.

#### 4. Conclusions

In summary, we have successfully demonstrated a 10-km length of the Cr-doped fibers by using a commercial drawing-tower method. The Cr-doped fibers had a 9- $\mu\text{m}$  core diameter and a 125- $\mu\text{m}$  cladding diameter. The ASE spectrum showed a broadband emission of 1.2 to 1.55  $\mu\text{m}$  and the central wavelength of the ASE spectrum shifted to a longer wavelength at 1.32  $\mu\text{m}$  when the pumping-light traveled through the length of the Cr-doped fiber. The advantages of using the drawing tower to fabricate the Cr-doped fibers are to have a better control on the core diameter and the fiber uniformity. These are beneficial when the Cr-doped fibers are integrated with the standard single-mode fibers and broadband WDM couplers for lightwave communication systems. This study makes it possible to fabricate a new Cr-doped fiber which has potential for being used as a broadband fiber amplifier to cover the bandwidths in the whole low-loss window of silica fibers.

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