Development of Broadband Single-Mode Cr- Doped Silica Fibers

Yi-Chung Huang, *member*, *IEEE*, Jau-Sheng Wang, Yen-Sheng Lin, Ting-Chien Lin, Wei-Lun Wang, Yu-Kuan Lu, Szu-Ming Yeh, Hsin-Hui Kuo, Sheng-Lung Huang, *Senior Member*, *IEEE*, and Wood-Hi Cheng, *Fellow*, *IEEE*

***Abstract*—The fabrication of broadband single-mode Cr-doped silica fibers (SMCDSFs) using the fiber drawing-tower method with the modified rod-in-tube technique is demonstrated for the first time. A single-mode characteristic of SMCDSF was observed when the propagation wavelengths were longer than 1310 nm. The transmission loss was about 8 dB/m at 1550 nm. The successful fabrication of SMCDSFs may facilitate the possibility for utilizing the SMCDSFs as a new generation broadband fiber amplifier to cover the bandwidths in the whole 1300-1600 nm range of low-loss windows of silica fibers.**

***Index Terms*—Broadband, fiber amplifier, fiber design and fabrication, single-mode fibers**

I. INTRODUCTION

ERBIUM-DOPED fiber amplifiers (EDFAs) are widely credited with enabling the huge transmission bandwidth and span distance of optical fiber communications during the last decade of the 20th century. Because EDFAs can effectively boost the amplitude of optical pulses traveling in optical fiber without converting those pulses to electrical signals, they can extend the range of the fiber optic link by many thousands of kilometers. The well-known EDFA provides gains in the C band, the L band, and the S band; which totaled 140-nm usable spectral bands. The other types of fiber amplifiers, such as praseodymium (Pr)-doped and thulium (Tm)-doped [1], [2] operate gain in the O band and in the S band, respectively. However, the gain bandwidths of the current Er-doped, Tm-doped, and Pr-doped fiber amplifiers cannot fully cover the whole 1300-1600 nm range with a single fiber amplifier. The transition-metal-doped materials, such as Ni^{2+} and Cr^{4+} ions [3], [4], have shown 300-nm broadband emissions. Recently, a Cr:YAG crystal fiber has been fabricated by the use of a co-drawing laser-heated pedestal growth (LHPG) method [5] or a drawing-tower technique [6], [7]. The Cr-doped fibers (CDFs) have demonstrated broadband emissions in the whole 1.3-1.6 μm range. However, the growth of core diameter below 10 microns by the LHPG method was difficult, and the uniformity of the core diameter varied greatly along growth direction. The drawing-tower technique equipped with rod-in-tube (RIT) design, by contrast, could provide better uniformity and smaller core diameter of CDFs [6], [7]. Recently, a single-mode Cr-doped silica fiber (SMCDSF) has been fabricated using the RIT when the wavelength of transmission light was longer than 1400 nm [8]. However, it cannot cover the typical optical communication band of 1310 nm.

In this study, we improve the fabrication of a SMCDSF by employing the RIT method with the additional modification of using a smaller diameter Cr:YAG single crystal rod. A single-mode characteristic of SMCDSF was demonstrated when the wavelengths of transmission light were longer than 1310 nm, which covered the typical optical communication band. A high-resolution transmission electron microscope (HRTEM) was employed to examine the microstructure of the core in SMCDSFs. The images of HRTEM showed very low densities of nano-particales in the area about 2.5 μm away from the center of the core. In comparison with the previous works on multimode CDFs [6], [7], the transmission loss was improved about 8 dB/m at 1550 nm. The fluorescence spectrum showed two broadbands of 800 to 1200 nm and 1200 to 1600 nm which were attributed to Cr^{3+} and Cr^{4+} ions, respectively. The successful fabrication of SMCDSFs may be one step forward towards the achievement of utilizing the SMCDSFs as ultra-broadband fiber optical amplifiers to cover the bandwidths in the whole 1300 to 1600 nm range of low-loss and low-dispersion windows of silica fibers and a broadband source for enabling high resolution in optical coherence tomography (OCT).

II. FABRICATION OF SINGLE-MODE Cr -DOPED SILICA FIBERS

A commercial grade <111> YAG rod doped with 0.25 wt % Cr used as a core rod was obtained from CASIX. The initial

Manuscript received January 8, 2010. This work was partially supported by the Department of Industrial Technology of MOEA under the Contract 97-EC-17-A-07-S1-025, the National Science Council under the Contract NSC97-2221-E-110-48-MY3, and the MOE Program of the Aim for the Top University Plan.

Y. C. Huang is with the Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, 106, Taiwan and Department of Photonics, National Sun Yat-Sen University, Kaohsiung, 804, Taiwan (e-mail:oris@mail.nsysu.edu.tw).

J. S. Wang, T.C. Lin, W.L. Wang, Y.K. Lu, S.M. Yeh, and W.H. Cheng are with the Department of Photonics, National Sun Yat-Sen University, Kaohsiung, 804, Taiwan (whcheng@mail.nsysu.edu.tw).

S.L. Huang is with the Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, 106, Taiwan.

Y.S. Lin is with the Department of Electronic Engineering, I-Shou University, Kaohsiung County, 840, Taiwan.

H.H. Kuo is with the Department of Electrical Engineering, National University of Kaohsiung, Kaohsiung, 811, Taiwan.

dimension of the Cr-doped YAG crystal rod had a length of 0.03 m and a diameter of 500 μm. The Cr-doped YAG crystal was grown into a diameter of a 290 μm with a length of 0.12 m by the LHPG method. A CO_2 laser beam created a molten zone on the top of the source rod. The seed crystal was dipped into the molten zone and slowly withdrawn, pulling the growing crystal from the melts [9]. Furthermore, the source rod was pushed upwards into the molten zone so as to maintain the uniformity of growing crystals. A preform was made using the grown Cr:YAG rod as core and the silica tube as cladding. A silica tube of outer and inner diameters of 20 and 7 mm, respectively, was necked down in one end by lathe to yield a preform. The 290-μm Cr:YAG rod then was placed in the center of the silica tube. The assembled preform was clamped utilizing the chuck of the preform feeding unit within the drawing tower, which was equipped with an internal pressure control. Figure 1 shows a schematic diagram of a Cr-doped YAG preform.

The CDFs were drawn at approximately 2280°C by using the Nextrom OFC 20 fiber drawing tower. The drawing speed was set at around 10 m/min. The utilization of pressure control on the preform aids in collapsing the tube at a proper temperature while maintaining circularity of the core. The CDFs were finally coated with dual layers of ultraviolet (UV) curable acrylate for maintaining a pristine surface during take-up and storage.

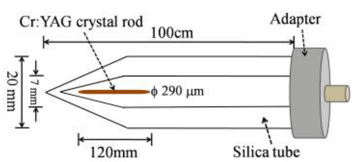

Fig. 1. Schematic diagram of a Cr-doped YAG preform with pressure control.

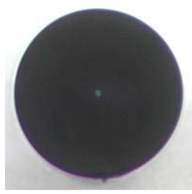
Fig. 2. Photograph of the cleaved end with a 5-μm-diameter core.

III. MEASUREMENTS AND RESULTS

1500 meters of the SMCDSFs have been drawn by using the drawing-tower technique. The core diameter of a SMCDSF was 5-μm with a 125-μm cladding, as shown in Fig. 2. The refractive index was measured by using commercial equipment, EXFO NR9200. The refractive-index of the CDF was the $n_{core} = 1.495$ and an index difference of $\Delta = 2.61\%$.

Figure 3 shows the measured far-field patterns of SMCDSFs at various wavelengths. A 0.5-m SMCDSF was spliced with a single-mode patch cord that was attached to a light source by a mechanical splicer for the measurement of the far-field pattern. In order to eliminate the cladding effect, macro-bending with the facilitation of refractive index matching gel was employed during the measuring process. From the measured far-field patterns, a single-mode characteristic of SMCDSF was clearly observed when the propagation wavelengths were longer than 1310 nm.

The microstructure of SMCDSFs was examined using a HRTEM (JEOL JEM-3010) equipped with a LaB_6 electron gun operating at 300 kV, as shown in Fig. 4 . It revealed that very low densities of crystalline nanostructures in the area about 2.5-μm away from core were uniformly distributed in a SiO_2 amorphous matrix. The existence of the crystalline structure was verified by the selected area electron diffraction (SAED) pattern taken from the large area to include enough nano-crystals, as shown in Fig. 4(d). The enlarged area in Fig. 4(b) shows the lattice parameter C_0 = 0.289-nm of the nano-crystals which were identified to be γ-Al_2O_3 (space group Fd3m) [10]. The microstructure of the interface between core/cladding areas was nearly amorphous without crystal structure, as shown in Fig. 4(c).

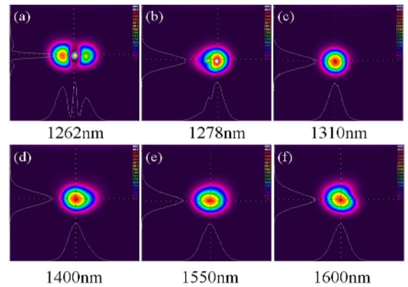

Fig. 3. The far-field patterns of CDF at different launching wavelengths.

To measure the composition of the SMCDSFs, an electron probe X-ray micro-analysis (EPMA, JXA-8900R) method was used. The relative weight percentage of silica and Cr in core was estimated to be around 83.56% and 0.025%, respectively. Therefore, Cr was still present in the central area of the core after being drawn.

A standard cutback technique was employed to characterize the transmission loss of the SMCDSFs. Firstly, a 1.05-m-length SMCDSF was spliced with a single-mode patch cord by a mechanical splicer for the measurement of the transmission loss. Then, we fixed the patch cord to a tunable laser source. Light powers in log scale were measured from the samples, 105-cm and 65-cm in length. The powers were subtracted and then divided by the length difference of 40-cm cutback in order to infer the true dB/cm core transmission value. Figure 5 shows the low transmission losses were 15 dB/m and 8 dB/m at 1310 nm and 1550 nm, respectively. The propagation loss of the Cr-doped crystal rod before fiber drawing was 2 dB/m. The peak around 1400 nm is attributed to the absorption of OH-ion. The loss of Cr:YAG-doped fiber is still relatively higher than those of Er:YAG-doped fiber made from Ballato's group [11].

A near-field scanning optical microscope (NSOM, NT-MDT) equipped with 1064-nm and 532-nm lasers as the excitation sources was used to measure the fluorescence spectrum of the SMCDSFs. The fluorescence spectrum of the SMCDSFs pumped by 1064-nm showed a peak emission about 1208 nm and extended to 1600 nm, as illustrated in Fig. 6 by the solid line. The dashed line spectrum in Fig. 6 reveals the emission of SMCDSF while pumped by a 532-nm light source. It showed a peak emission around 1000 nm covering the wavelength range 800-1200 nm. Due to coexistence of Cr^{3+} and Cr^{4+} ions, the bands of 800-1200 nm and 1100-1600 nm were dominated with Cr^{3+} and Cr^{4+} ions, respectively. In comparison with previous publications on multimode CDFs [6], [7], the measured fluorescence spectral bandwidths were extended from mainly near-infrared (NIR) to infrared (IR) regions (800-1200 nm and

1100-1600 nm). To increase the fluorescence efficiency, a modified process toward the formation of uniform nano-crystalline of Cr:YAG with high concentration in silica fiber is under active investigation.

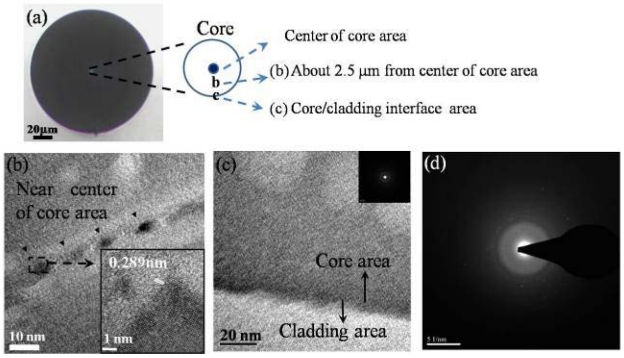

Fig. 4. (a) Photograph of polished endface of SMCDSF and HRTEM images, (b) the area near the center of the core with inserted images showing selectively enlarged areas of nano-crystalline particles, (c) near the interface between core/cladding, and (d) SAED pattern of the area near center of the core.

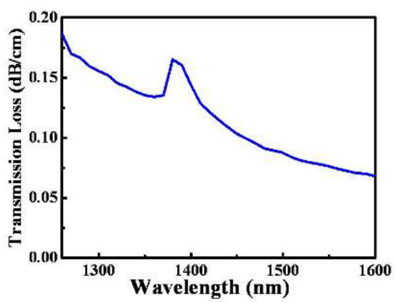

Fig. 5. The transmission loss of SMCDSFs.

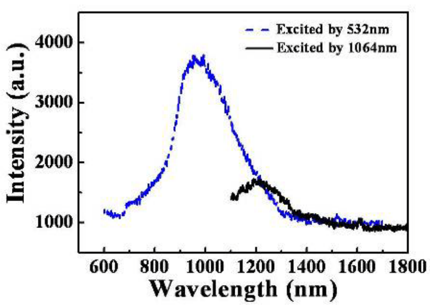

Fig. 6. The fluorescence spectrum of SMCDF pumping by 1064-nm (solid-line) and 532-nm (dashed-line).

IV. Conclusion

A SMCDSF silica-based fiber with its emission wavelength extending from 800 to 1600 nm under dual pumping wavelengths was demonstrated by using a modified RIT method along with fiber drawing-tower technique. The SMCDSFs had a 5-μm core and a 125-μm cladding. The far-field pattern measurements indicated the single-mode characteristic when the propagation wavelength was longer than 1310 nm. From the HRTEM images, it was clear that the core of SMCDSF was not pure single crystalline structure but mostly amorphous structure. This could be identified by the profile of relative weight percentages of the core. The core of SMCDSF showed a low density and uniform distributed of γ-Al_2O_3 nano-crystalline structure, which was surrounded by a SiO_2 amorphous matrix. The transmission losses were 15 dB/m and 0.08 dB/m at 1310 nm and 1550 nm, respectively.

The improvements in eliminating OH-ion absorption of SMCDSF and reducing transmission loss to fractional dB per meter are the major topics in the development of broadband single-mode Cr-doped silica fibers. In order to decrease the loss of SMCDSF, the diameter of the Cr:YAG rod has to match the inner diameter of the cladding silica tube as closely as possible. To improve the fluorescence efficiency, a refining process toward the formation of uniform nano-crystals of Cr:YAG with a high concentration in silica fiber is necessary and currently under investigation. This work is the first in published to propose a broadband single-mode Cr-doped silica fiber. This study integrates both the LHPG and drawing-tower techniques to achieve the single-mode Cr-doped silica fiber. The demonstration of SMCDSFs makes it possible for utilizing the SMCDSFs as a new generation broadband fiber amplifier to cover the full bandwidth in the low-loss window of silica fibers, a tunable NIR fiber laser for sensor application, and a broadband source for high resolution OCT.

References

[1] Y. Ohishi, T. Kanamori, T. Kitagawa, S. Takahashi, E. Snitzer, and G. H. Sige, Jr., "Pr^{3+}-doped fluoride fiber amplifier operating at 1.31μm," Opt. Lett. vol. 16, pp. 1747-1749, Nov. 1991.

[2] T. Kasamatsy, Y. Yano, and H. Seller, "1.50-μm-band gain-shifted thulium-doped fiber amplifier with 1.05- and 1.56-μm dual-wavelength pumping," Opt. Lett. vol. 24, pp. 1684-1686, Dec. 1999.

[3] T. Suzuki and Y. Ohishi, "Broadband 1400 nm emission from Ni^{2+} in zinc-alumino-silicate glass," Appl. Phys. Lett. vol. 84, pp. 3804-3806, May 2004.

[4] S. Tanabe and X. Feng, "Temperature variation of near-infrared emission from Cr^{4+} in aluminate glass for broadband telecommunication," Appl. Phys. Lett. vol. 77, pp. 818-820, Aug. 2000.

[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 Cr^{4+}:YAG crystal fiber amplifier," Opt. Lett., vol. 30, pp. 129-131, Jan. 2005.

[6] Y. C. Huang, J. S. Wang, Y. K. Lu, W. K. Liu, K. Y Huang, S. L. Huang, and W. H. Cheng, "Preform fabrication and fiber drawing of 300 nm broadband Cr-doped fibers," Opt. Exp., vol. 15, pp. 14382-14388, Oct. 2007.

[7] Y. C. Huang, Y. K. Lu, J. C. Chen, Y. C. Hsu, Y. M. Huang, S. L. Huang, and W. H. Cheng, "Broadband emission from Cr-doped fibers fabricated by drawing tower," Opt. Exp., vol.14, 8492-8497, Sept. 2006.

[8] Y.C. Huang, J.S. Wang, T.C. Lin, Y.S. Lin, W.L. Wang, Y.K. Lu, Y.C. Lin, S.M. Yeh, H.H. Kuo, S.L. Huang, and W.H. Cheng, "Fabrication and Characteristics of Ultra-Broadband Singlemode Cr-Doped Fibers," OFC, San Diego, CA, OMG5, Mar. 2010.

[9] D.H. Yoon, "Crystal growth of the oxide fiber single crystal for optical applications," Opto-Electronics Review, vol. 12(2), pp. 199–212, Sept. 2004.

[10] 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, "Nanostructure formation of double-clad Cr^{4+}:YAG crystal fiber grown by co-drawing laser-heated pedestal," J. Crystal Growth vol. 289, pp. 515-519, Apr. 2006.

[11] J. Ballato, T. Hawkins, P. Foy, B. Kokuoz, R. Stolen, C. McMillen, M. Daw, Z. Su, T. M. Tritt, M. Dubinskii, J. Zhang, T. Sanamyan, and M. J. Matthewson, "On the fabrication of all-glass optical fibers from crystals," J. Applied Physics, vol. 105, pp. 053110, Mar. 2009.