Tetrahedral-Cr Enhancement Employing Dielectric Coating for Higher Gain of Broadband Cr-Doped Fiber Amplifiers

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Abstract: We report gross gain of 8.4-dB for 300-nm broadband single-mode Cr-doped crystalline core fiber (SMCCDF) employing dielectric coating, thermal annealing, and polarization pumping techniques. This gross gain is the highest yet demonstrated of the SMCDCCFs.

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1. Introduction

The tetrahedral chromium doped with yttrium aluminum garnet (Cr^{4+}:YAG) are the main concentrations to provide gain in the single-mode Cr-doped crystalline core fibers (SMCDCCFs) and exhibit a broadband emission of 1300-1600 nm [1-2]. The SMCDCCF may be possible functions as broadband amplifiers for utilization over the fiber low-loss transmission. However, it is difficult to maintain enough tetrahedral chromium (Cr^{4+})-ions in the Cr:YAG because the chromium oxide is highly volatile during high temperature laser-heated pedestal growth (LHPG) process [3]. Furthermore, the highest chromium doping concentration in a 1-mm bulk of the Cr:YAG does not more than 0.1wt%. Therefore, the gain improvement by developing high concentration of Cr^{4+}-ions in the Cr:YAG material is essential to develop high-performance broadband fiber amplifiers.

In previous study, the Cr^{4+}-ion enhancement in the SMCDCCFs leading to higher-gain broadband fiber amplifiers by thermal annealing was reported [2]. Despite previous study on the Cr^{4+}-ion enhancement in the Cr:YAG bulk material [3] and SMCDCCF [2] using thermal annealing technique, limited Cr^{4+}-ion enhancement is still not enough to provide gain for use in fiber transmission system. In this study, higher gain of the SMCDCCFs with higher Cr^{4+}-ion in the Cr:YAG rod by using dielectric coating and polarization pumping are presented. The dielectric coating of the chromium oxide (Cr_2O_3) and calcium oxide (CaO) on the surface of the Cr:YAG rod and then co-fused the Cr:YAG rod to grow the SMCDCCF with thermal annealing was employed. It was well known that the divalent cation of Ca^{2+} was evaluated for the charge compensator in the Cr:YAG to increase the Cr^{4+} concentration [4]. The gross gains of 4.7 and 6.7-dB with 20-cm-length of SMCDCCFs were measured without and with Cr_2O_3/CaO coating, respectively. The 42% gain improvement was mainly achieved by enhancing the Cr^{4+}-ions up to 1.2 times in the SMCDCCF by coating. The additional 11% gain improvement by thermal annealing and further 25% gain improvement by polarization pumping source for the SMCDCCF was obtained the gross gain up from 4.7-dB to 8.4-dB. Further study employing suitable dielectric coating and longer length (<30cm) of fiber to achieve more than 10-dB gain of the SMCDCCFs is currently under investigation and will be present. That is possible to achieve higher gain of the SMCDCCFs as broadband fiber amplifiers for practical use in the next-generation fiber transmission systems.

2. Fabrication

Figure 1 shows an electron-beam evaporation system for the chromium concentration coating on the Cr:YAG rods with <111> crystal axis. A 99.9% Cr_2O_3 and a 99.9% CaO were used as target materials. The high-energy electron beam was turned into 270^o and hit on the target and then reached the melting point of the material. The 300-μm Cr:YAG rods were mounted on the rotating substrate. After the atom evaporates, a brown Cr_2O_3/CaO film was formed on those rods. In this coating process, the single-side and double-side coatings of the Cr_2O_3/CaO film with thickness of 900-nm were obtained, which were measured by an atomic force microscope. Then, the coated Cr:YAG rods would be re-growth by online LHPG system to diffuse the Cr- and Ca-ions into the core of SMCDCCF. This online LHPG system was integrated with a 60W-CW CO_2 laser of ± 0.4% power fluctuation, few mirrors, a beam expander, and a growth chamber, as shown in Fig. 2(a). The structure of the growth chamber was designed to narrow the molten zone with uniform distribution azimuthally. The 300-μm Cr:YAG rod with Cr_2O_3/CaO coating were reduced to 80-μm and 25-μm core diameter of single crystal fibers by high-temperature LHPG multi-growth. In this work, the symmetrical molten zone and the suitable growth speed ratio should be demanded. Therefore, we were able to obtain longer fiber length with better core uniformity of the SMCDCCFs. In order to transform the Cr-ion from Cr^{3+}(octa) to Cr^{4+}(tetra) [2], the fiber samples were annealed under air environment for 12 hours at 1000°C. Finally, the 25-μm core and 20-cm fiber length of the Cr:YAG fibers had been clad with the high-index glass tubes (N-SF57, SCHOTT) to form the SMCDCCFs during high-temperature laser fusing, as shown in Fig. 2(b). The single-mode (LP_{01}) characteristic of this SMCDCCFs were clearly observed at 1.4-μm wavelength by the far-field pattern measurement [1, 2].

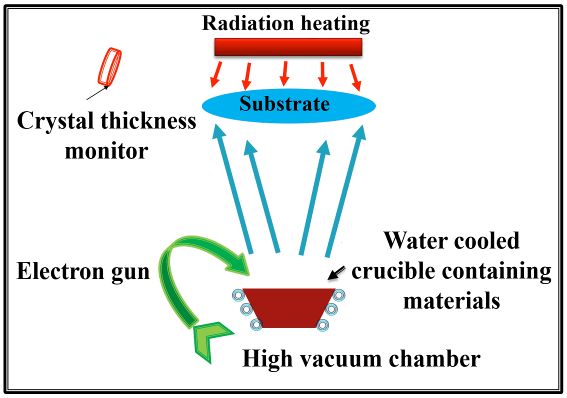


Fig. 1. Electron-beam evaporation process.

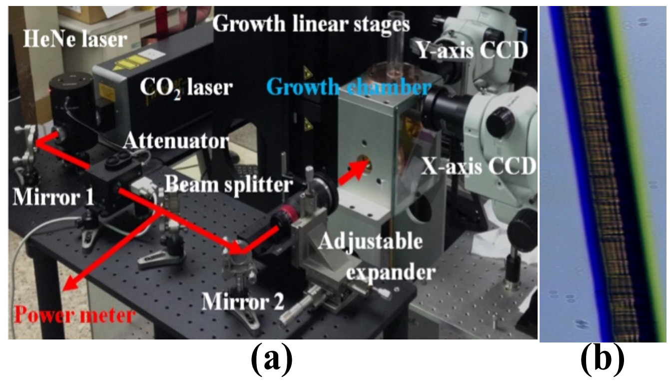
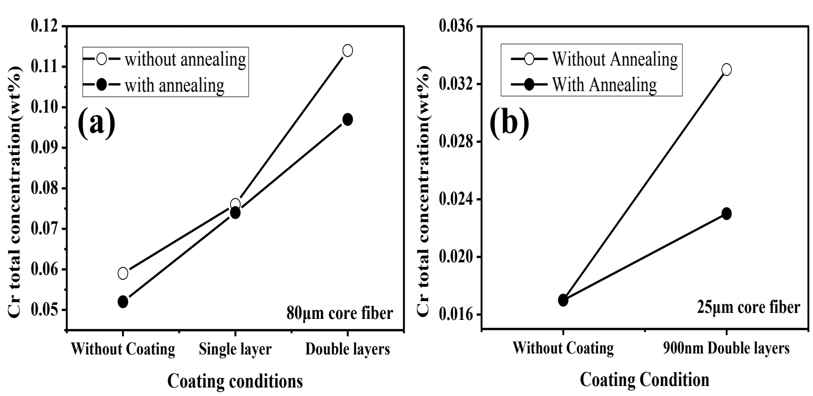


Fig. 2. (a)The online LHPG system, (b) SMCDCCF with coating film.

3. Measurements and Results

3-1 Total Cr-Concentration by Cr_2O_3/CaO coating and thermal annealing

An Electron Probe X-ray Microanalyzer (EPMA) was used to quantify the elements of SMCDCCF at different Cr_2O_3/CaO coating conditions. Figure 3(a) and (b) showed the total concentration of Cr-ion as a function of different coating and annealing conditions. The total concentrations of Cr-ion in 80-μm Cr:YAG fibers were measured 0.056wt%, 0.075wt%, and 0.113wt% without, with single-layer, and with double-layers Cr_2O_3/CaO coating, respectively. After annealing, the total concentrations of Cr-ion in 80-μm Cr:YAG fibers were reduced and measured 0.051wt%, 0.073wt%, and 0.096wt% without, with single-layer, and with double-layers Cr_2O_3/CaO coating, respectively, as shown in Fig. 3(a). The decreased Cr-ion concentration after annealing process was due to the Cr-ion was slowly volatilize at high temperature environment. For 25-μm SMCDCCFs in Fig. 3(b), the total concentration of Cr-ion was increased from 0.017wt% to 0.033wt% with 900-nm double-layers Cr_2O_3/CaO coating, and then decreased from 0.033wt% to 0.022wt% after thermal annealing. Based on the superconducting quantum interference device (SQUID) results [2], the Cr^{4+}(tetra) recovered from the Cr^{3+}(octa) and the relative concentration ratio of the Cr^{3+}/Cr^{4+}-ion in the Cr:YAG was 52/48 during thermal annealing at 1000°C. The improvement of Cr^{4+}-ion as a function of different conditions, as shown in Fig. 4. The Cr^{4+}-ion improvement of 80-μm Cr:YAG fibers were 131% and 206% with thermal annealing for single-layer and double-layers coating, respectively. The Cr^{4+}-ion improvements of 25-μm SMCDCCFs with thermal annealing were 55% and 120% without and with double-layers coating, respectively. This indicated that the Cr^{4+}-ion improvement up to 1.2 times for double layer coating



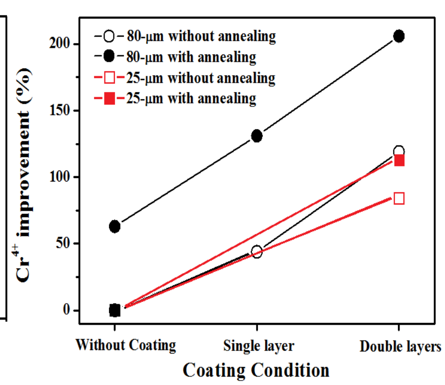


Fig. 3. Comparison of chromium concentration for (a) 80μm and (b) 25μm core fibers. Fig. 4. Cr^{4+} improvements of 80μm and 25μm fibers.

3-2. Fluorescence Intensity and Gain Measurements

For measuring the fluorescence of fiber samples, a 1.06-μm Nd:YAG laser with 600 mW was employed as a light source. Figure 5 showed the fluorescence spectrum as function of wavelengths with different samples. The fluorescence spectrum from 1300 to 1600 nm were attributed to Cr^{4+}-ion at tetragonal site. The fluorescence intensity of 80-μm Cr:YAG fiber with double-layers Cr_2O_3/CaO coating and annealing was significantly improved 1.5 times compared with the 80-μm Cr:YAG fiber without coating and annealing process at the wavelength of 1380 nm. This was attributed to two reasons: (1) total Cr-ion concentration increased;(2) the co-dopants of Ca^{2+} could serve as charge compensators to transform smoothly from Cr^{3+} to Cr^{4+} [4], resulting the higher fluorescence intensity. To characterize the gross gain of the SMCDCCFs, an Nd:YAG laser pumping source at 1.06-μm and a 1.4-μm signal source were employed and then measured by a polarization controller. The polarization of transmitted light for Cr^{4+}:YAG is very crucial to the amplifier performance. The Cr^{4+}:YAG fibers were the best output performance when the polarization of both the pumping- and signal-light were parallel to the <111> crystal axis of YAG [5]. Then, the amplified signal light by the SMCDCCF was detected by an optical spectrum analyzer. The gross gain of fiber amplifiers is defined as $G = 10*\log[(P_{s+p} - P_p)/P_s]$, where the P_s, P_p, and P_{s+p} are the input signal light, optical pumping light, and both input signal and optical pumping light, respectively [1,2]. Figure 6(a) showed the measured gross gain as a function of pumping power of the SMCDCCFs. The gross gains of 4.7 and 6.7-dB with 20-cm-length of SMCDCCFs were measured without and with Cr_2O_3/CaO coating, respectively. The 42% gain improvement was mainly achieved by enhancing the Cr^{4+}-ions up to 1.2 times in the SMCDCCF by coating. The additional 11% gain improvement by annealing and further 25% gain improvement by polarization pumping for the SMCDCCF was obtained the gross gain up from 4.7-dB to 8.4-dB. For practical application in fiber transmission of the SMCDCCF, a testing system of 25-Gb/s data rate was employed to investigate the performance of long-haul fiber transmission over 30-km. Eye diagram was obtained with clear eye opening and without waveform distortion was observed, as shown in Fig. 6(b).

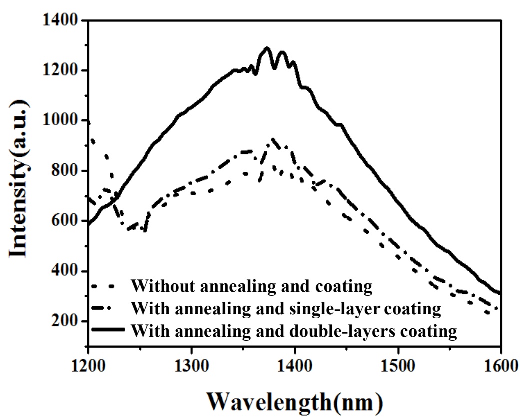


Fig. 5. Fluorescence spectrum of SMCDCCFs.

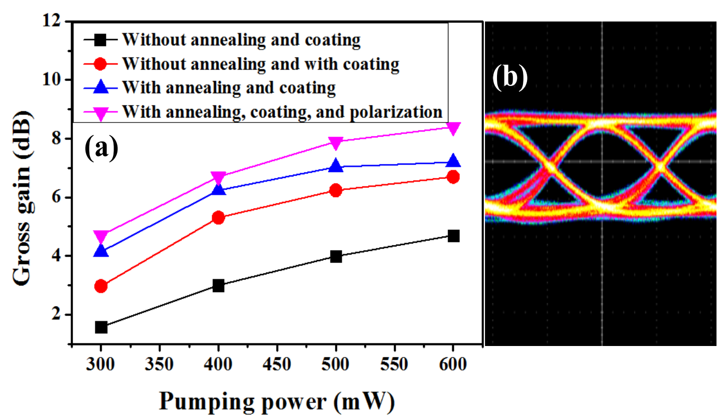


Fig. 6. (a) Measured gross gain of SMCDCCFs, (b) eye diagram of SMCDCCF.

4. Conclusion

In summary, the higher gain of the SMCDCCFs for tetrahedral chromium enhancement of the Cr:YAG employing dielectric Cr_2O_3/CaO coating, thermal annealing, and polarization pumping techniques were proposed. The 8.4-dB gross gain of the SMCDCCF was demonstrated, which was the highest gain yet reported of the SMCDCCFs. A 25-Gb/s error-floor free data transmission was also demonstrated. Further study to achieve more than 10-dB gain of the SMCDCCF for use in the next-generation fiber transmission systems is currently under investigation and will be presented.

5. Acknowledgement

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6. References

[1] C.N. Liu, *et. al.*, "Higher gain of single-mode Cr-doped fibers employing optimized molten-zone growth," *J. Lightw. Technol.*, **35**, 4930-4936 (2017).

[2] C.N. Liu, *et. al.*, "Higher gain of broadband single-mode Cr-doped fiber amplifiers by tetrahedral-Cr enhancement," OFC, Mar. 3-7, San Diego, CA (2019).

[3] X. Xua, *et. al.*, "Spectroscopic and thermal properties of Cr,Yb:YAG crystal," *J. Cry. Growth*, **262**, 317-321 (2004).

[4] I.T. Sorokina, *et. al.*, "Anomalous absorption saturation in Cr,Mg:YAG and Cr,Ca:YAG," CLEOE, Sept. 10-15, Nice, France (2000).

[5] Y. Sato, *et. al.*, "Model for the Polarization Dependence of Saturable Absorption Characteristics in Cr^{4+}:YAG," LIC, Jun. 20-23, Bucharest, Romania (2017).