Record Gain of 18-dB for Broadband Single-Model Cr-Doped Crystalline Core Fiber by Small Core Diameter

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Abstract: We demonstrate record gain of 18-dB broadband single-mode Cr-doped crystalline core fiber employing small core diameter. The gain-per-unit-length is 90 dB/m, which is higher than currently achieved Er and Bi-doped fibers of 0.6 - 3 dB/m.

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1. Introduction

The channel numbers of WDM are determined by the gain bandwidth of Er, Tm, Pr, and Bi-doped fiber amplifiers. However, the usable bandwidths provided to these fiber amplifiers are not enough to fully cover the low-loss transmission windows with a single fiber amplifier. Therefore, it is highly desirable to develop a single broadband fiber amplifier with gain bandwidth covering the low-loss transmission windows of optical fibers. Recently, single-mode chromium-doped crystalline core fibers (SMCDCCFs) have been explored and fabricated as the possible candidate as broadband amplifiers for covering the interval from 1.3 to 1.6-µm [1, 2].

The pump to signal conversion efficiency (PSCE) of the core 25-µm SMCDCCF was very lower of less than 1%, which was obstacle for practical use in broadband fiber amplifiers [2]. According to the numerical aperture of the SMCDCCFs, core diameter reduction of the SMCDCCF may increase coupling efficiency (CE) of pumping power and hence improve PSCE for higher gain of the SMCDCCFs. In this study, higher CE, PSCE, and gain of the SMCDCCFs fabricated by a smaller core diameter of 13-µm is reported by employing a novel forecast-auxiliary-line (FAL) assistance in laser-heated pedestal growth (LHPG). Employing the FAL assistance, we enable to precise controlling and stabilizing laser power for constantly maintaining conical molten-zone shape during the LHPG process to grow smaller core diameter and longer length of the SMCDCCF.

In this study, we demonstrate a higher gain of 18-dB for SMCDCCF in a smaller core diameter of 13-µm. This is a 64% gain improvement higher than the previous report of 11-dB for the SMCDCCFs in a core diameter of 25-µm [2]. The gain-per-unit-length of the SMCDCCF is 90 dB/m, which is much higher than the currently achieved 0.6 – 3 dB/m of Er and Bi-doped fibers [3, 4], as shown in Table 1. The gain and gain-per-unit-length are the highest yet reported of the SMCDCCF. This record gain is obtained due to (1) a precise conical molten-zone shape in growth process and (2) optimization of the Cr^{4+} concentration.

Table 1. Comparison of net gain, gain-per-unit-length, and core diameter for different doped fibers.

Reference	Type	Net Gain (dB)	Gain-Per-Unit-Length (dB/m)	Core Dia. (µm)
2021 JLT [2]	CDF	11	32	25
2021 OFC [4]	BDF	38	0.57	11
2022 IJCS [3]	EDF	39	3.25	1.2
This study	CDF	18	90	13

* CDF = Cr-doped fiber, BDF = Bi-doped fiber, EDF = Er-doped fiber.

2.1 Fabrication of SMCDCCF

Figure 1 shows an online growth system of the LHPG system [1, 2]. A continuous-wave CO_2 laser with 4.4-mm beam diameter was used to grow fiber with power fluctuation less than ± 0.4%. The growth chamber was designed by focusing the laser power to the optimized molten zone with uniform distribution azimuthally. A Cr:YAG source rod was reduced from diameter 300-µm to 66-µm, and then was reduced to 13-µm diameter of the single crystal fibers by high-temperature LHPG multi-growth. The 13-μm single crystal fibers were inserted into a glass tube to form the SMCDCCFs. Finally, the Cr:YAG fibers for different core diameters with different lengths were obtained.

In the LHPG process, the pulsed energy of CO_2 laser is an important grow parameter. Any noise may affect the stability of the laser operation. Figure 2 shows the laser power as a function of cycle time. The pulse laser exhibited an energy gap without any adjustment, as shown the black lines in Fig. 2 [2]. It is difficult to make accurate adjustment for stabilizing laser power even with the adjustment the laser power in time. The manual adjustment to control the power is necessary as the power of the line drops. However, it is difficult to make precise manual adjustment. In this work, a novel forecast-auxiliary-line (FAL) is proposed which stabilizes power to the average line. After the FAL assistance, the power gap from peak to peak is only 0.3W (red line) of Fig.2 [2]. The gap is a significant 66% lower than with manual adjustment. Therefore, we are able to use the FAL in the LHPG process for fabricating smaller core of the SMCDCCFs.

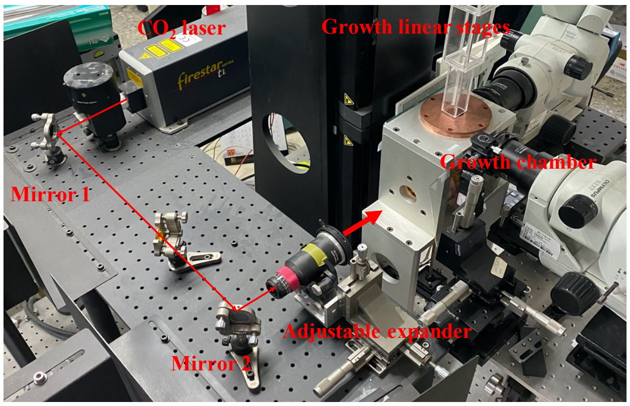

Fig.1 Laser-heated pedestal growth system.

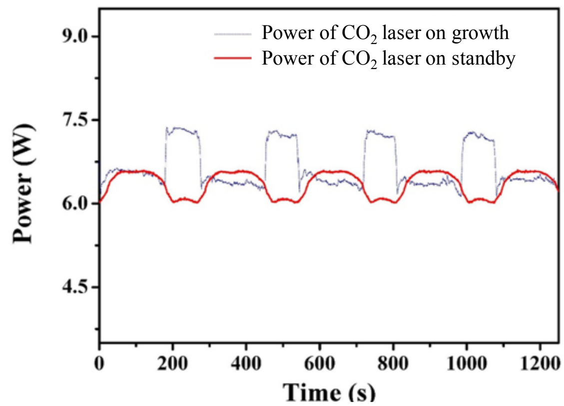

Fig.2 Prediction laser power: original power (black) and power with FAL control (red).

Two different SMCDCCFs were fabricated as listed in Table. 2. As a parameter to assess the growth quality, we use the standard deviation of the core diameter for the SMCDCCFs in the LHPG process. The crystal fibers that have smaller standard deviation of diameters can provide better light path to reduce losses, leading to the higher fluorescence intensity and gain. A standard deviation below 0.6 μm was used a limit to indicate a good grow quality of the SMCDCCF in the LHPG process [2].

Table 2. Four different fabrication parameters of the SMCDCCFs.

Fiber index	**A**	**B**
Core diameter (μm)	25	13
Cladding diameter (μm)	300	300
Fiber length (cm)	34	20
Core diameter standard deviation (μm)	0.32	0.60
Annealing	1000°C 12 hrs	Without
Cr_2O_3/CaO film coating (nm)	Cr_2O_3:560 CaO:2800	Cr_2O_3:560 CaO:2800

2.2 Coupling and signal to pump conversion efficiencies of SMCDCCF

Because of the coupling mode-mismatch from different core diameter size between SMCDCCF and single-mode fiber, we used a predictive control with a precise conical molten-zone shape in growth process to fabricate smaller core of 13-μm and reduce the coupling mode-mismatch effect, leading to a higher CE and PSCE. The PSCE defined as the ratio of output signal power to input pump power. The different core diameters of SMCDCCFs were butted coupling with a single-mode fiber by a mechanical splicer to measure the power rate between input and output power. Figure 3 shows the measured CE and PSCE for different core diameters. The PSCEs of the samples A and B were 0.3 and 1.4%, respectively. The CEs of the samples A and B were 15 and 52%, respectively. The result showed that the CE and PSCE significantly improved as fiber diameter reduced.

3. Measurements and Results

An Nd:YAG laser pumping source at 1.06-µm and a 1.4-µm signal source were employed and measured for different diameters of the Cr:YAG fiber. The amplified signal light by the SMCDCCF was detected by an optical spectrum analyzer. In this work of the CE measurements, the sample A of 25-µm Cr:YAG fiber was selected as the standard and compared with Cr:YAG samples of different diameter sizes. Figure 3 shows the CE and PSCE of Cr:YAG fiber for different core diameters. The CE significantly improved as fiber diameter reduced. Benefiting from the improvement of the CE, the PSCE was also improved as fiber diameter reduced. The PSCEs of the samples A and B were 0.3 and 1.4%, respectively. Comparison with the core diameter of the 25-µm SMCDCCF, the CE and PSCE of the 13-µm SMCDCCF are increased by 4.6 and 3.5 times, respectively. In this study the net gain of the SMCDCCF is measured as the ratio between the amplified output signal power and input signal power. The net gain of the SMCDCCF is simplify defined as $G = 10*\log[(P_{s+p})/P_s]$, where the P_s and P_{s+p} are the 1400-nm input signal power to the SMCDCCF, and total 1400-nm signal power at the end of the SMCDCCF, respectively [1, 2]. Figure 4 shows the measured net gain as a function of pumping power of the SMCDCCFs for different core diameters of 13 and 25-µm and fiber lengths of 20 and 34-cm with different coating and annealing conditions at a wavelength of 1400-nm, as listed in Table 2. The 20 and 34-cm lengths of the samples A and B were measured without and with annealing, respectively. In comparison to the samples A and B of the net gain 18-dB and 11-dB [2], respectively, the 64% net gain improvement of the sample A was mainly achieved by further CE and PSCE improvement. This result confirms that optimization of the Cr^{4+} concentrations for the SMCDCCFs by small core diameter, which provides the significant gain improvement.

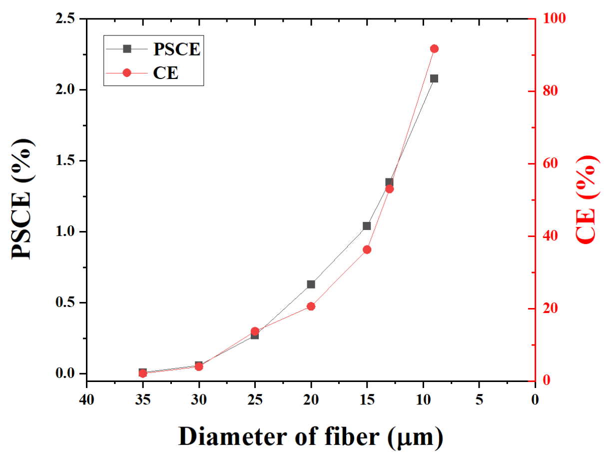

Fig.3 The measured CE and PSCE of Cr:YAG fiber.

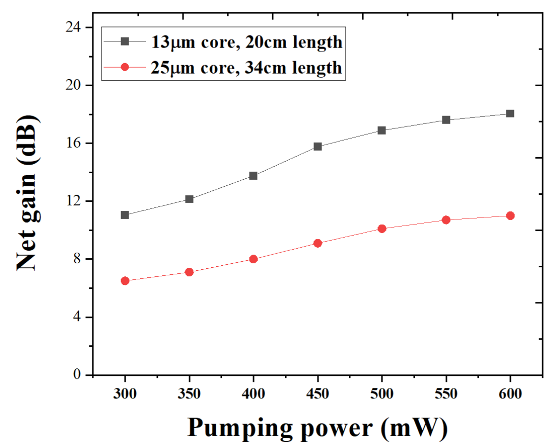

Fig.4 The gross gain as function of pumping power of Cr:YAG fiber.

4. Conclusions

In summary, we have demonstrated a record gain of 18-dB for 300-nm broadband SMCDCCFs employing a novel growth of smaller core diameter of the 13-µm fiber. The gain-per-unit-length efficiency of the SMCDCCF was about 90 dB/m, which was much higher than the currently Er and Bi-doped fibers of 0.6 – 3 dB/m [3, 4]. For improving the CE, PSCE, and gain, the technology of the core diameter reduction employing a novel FAL assistance in LHPG is effective. Further studies on reduction core diameter of the SMCDCCF to 9 µm, which could match a standard single mode fiber, and hence could improve coupling efficiency, power conversion efficiency, and gain. These studies are currently under investigation and will be presented.

5. Acknowledgement

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6. References

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