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Experimental results of high power Double-Pass, Double Clad EYDFA

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ABSTRACT

A high-power, double-pass (DP), and double-clad (DC) Erbium (Er)-Ytterbium (Yb) doped optical fiber amplifier (EYDFA) was fabricated and experimentally evaluated. Because optical amplifiers for space missions must achieve higher electrical-to-optical conversion efficiency in consideration of power consumption and heat generation, we focused on a DP optical fiber amplifier that can be expected to achieve high optical-to-optical conversion efficiency. Free-space optics and integrated design were adopted for a DP module and a Faraday mirror (FM) module, so as to ensure low transmission loss (high efficiency). The DP module including a tap mirror, isolators, and a polarizing beam splitter measured 70×50×22.5 mm in size, with transmission loss of 0.65 dB (from input port to pump combiner port) and 0.52 dB (from pump combiner port to output port). In contrast, the FM module was 40×37×18.5 mm in size, with round-trip transmission loss of 0.66 dB. The fabricated DP-DC-EYDFA achieved output power of around 7 W in the wavelength range from 1540 to 1560 nm and optical-to-optical conversion efficiency exceeding 32%. To the authors' knowledge, this is the highest output power ever recorded by a DP-DC-EYDFA. The measured polarization extinction ratio (PER) of the fabricated DP-DC-EYDFA was 23.6 dB without using PM EYDF. And in comparison with a single-pass DC EYDFA using the same EYDF, we obtained results showing that the conversion efficiency of the DP-EYDFA was at least 4.2% higher than that of the SP-EYDFA.

Keywords: Space optical communication, PM-EYDFA, double pass, double clad

1. INTRODUCTION

One of the most significant issues of space optical communication systems for the successor of the Japanese data relay system (JDRS) or future very high throughput satellites (vHTSs) is how to realize small size, weight and power consumption (SWaP) [1-2]. Even though achieving small SWaP is a major issue, increasing the output power of transmitting optical amplifiers is indispensable for long-distance and higher-rate data transmission as requested in these missions. Thus, the optical high-power amplifier (OHPA) plays the most important role in realizing small SWaP. When the output power of OHPAs becomes large, thus improving electrical-to-optical conversion efficiency, the efficiency from supplied electrical power to amplified optical output power is the only solution for not increasing power consumption. In addition, to avoid interference, adequate isolation between optical transmitters and receivers must be achieved by utilizing both wavelength and polarization. Therefore, realizing a polarization-maintained (PM), 10-W class and highly efficient OHPA is of primary importance [1]. Here, the OHPAs also play a prominent role in optical communication from the lunar region or deep space.

Focusing on OHPAs for space missions, output power exceeding 20 W was experimentally achieved in the United States, and a 6-W class prototype based on the experiments was developed for a planetary exploration mission [3]. In addition, OHPAs for satellites operating in geostationary orbit (GEO) or low Earth orbit (LEO) were also reported [4, 5]. At the same time, as a part of research and development programs in the European Space Agency (ESA), OHPAs including a 10-W class EYDFA are making progress through collaboration between ESA and private-sector corporations [6, 7]. All of these OHPAs achieved high power by applying an ordinary single-pass (SP) EYDFA that adopted DC Er-Yb doped optical fiber (EYDF), multi-mode (MM) high-power, and a high-efficiency laser diode (LD) based on indium gallium arsenide (InGaAs), along with clad pumping at the wavelength region between 915 and 980 nm.

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In the EYDFA, the absorption bandwidth and intensity of excitation light are significantly improved by the co-doped sensitization effects of Yb and Er. However, due to the occurrence of reverse energy transfer from Er to Yb or the excited state absorption (ESA) of Er, the optical-to-optical conversion efficiency, that is, the efficiency from pumping light to signal light, is inevitably low compared with those doped with only Er. Here, cascade-, hybrid- and DP-amplification systems were proposed, so as to improve the performance of Er-doped optical fiber amplifiers (EDFAs) [8-12]. Among such systems, the DP-amplification method was considered a very effective way of improving the optical-to-optical conversion efficiency because amplified light passes through EDF twice. Regarding DP-EDFAs or EYDFAs, 0.5 W output power was achieved by using a single-core and core-pumping-type EDF [13]. In addition, output power reached 1 W by adopting a DC and the first clad-pumping-type EYDF [14]. As such much higher output power has never been reported so far, however, it is unclear whether the DP-amplification method is suitable for the 10-W class OHPAs. Based on this background, the purpose of this study is to experimentally confirm the applicability of the DP-DC-EYDFA to the 10-W class OHPAs for space optical communications.

2. DESIGN AND FABRICATION OF THE DP-DC-EYDFA

Figure 1 shows a block diagram of the DP-DC-EYDFA that was designed and fabricated in this research. Linearly polarized signal light is launched from the input port of the DP module. After passing through a tap mirror, an isolator (ISO), and a PBS, the signal light is led to a pump combiner followed by an EYDF (with both the pump combiner and EYDF maintaining non-polarization). The signal light is then amplified while traveling through the EYDF. The amplified signal light is reflected by the FM module (in which polarization is rotated by 90 degrees by passing through the Faraday rotator twice). The reflected signal travels back and is returned to the DP module. It should be noted that the amplified signal's state of polarization returns to being linear and orthogonal to that of the input signal [13]. (This means that polarization-maintaining (PM) operation is enabled without using active PM fibers due to the use of the FR module.) Therefore, we can extract all portions of the amplified signal from the reflection port of the PBS in the DP module. The output light from the DP module is derived from a fiber collimator. The EYDF is clad-pumped at a wavelength of 940 nm by using the pump combiner. Because the signal is amplified twice in the EYDF, the amplifier is likely to be operated in a saturation region. Hence, both high power and efficient operation are possible in cases where loss of the DP module and FP module can be reduced.

Figure 2 shows an external view of the DP-DC-EYDFA. In this research, the DP and FM modules were designed and fabricated based on high-precision free-space optics to acquire lower optical loss for higher efficiency as the OHPA. The DP module was 70×50×22.5 mm in size, and the optical losses at 1550 nm were measured to be 0.65 dB (from input port to pump combiner port) and 0.52 dB (from pump combiner port to output port (collimator)), respectively. The FM module had dimensions of 40×37×18.5 mm and its round-trip loss was only 0.66 dB. In this way, such a low optical loss was achieved by applying high-precision free-space optics and integrated design. Table 1 lists the commercially available MM LD, DC-EYDF, and pump combiner utilized in the fabricated DP-DC-EYDFA. Among them, commercially available DC-EYDFs are extremely sensitive to a radiation environment. We will therefore apply radiation-hardening EYDF in the future [15].

Table 1 Commercially available components utilized in the DP-DC-EYDFA

Item	Supplier	Model number
Pump LD	II-VI	BMU30-940-01-R20
DC-EYDF	Nufern	SM-EYDF-10P/125-XP
Pump combiner	Gooch and Housego	TFB 550211B71

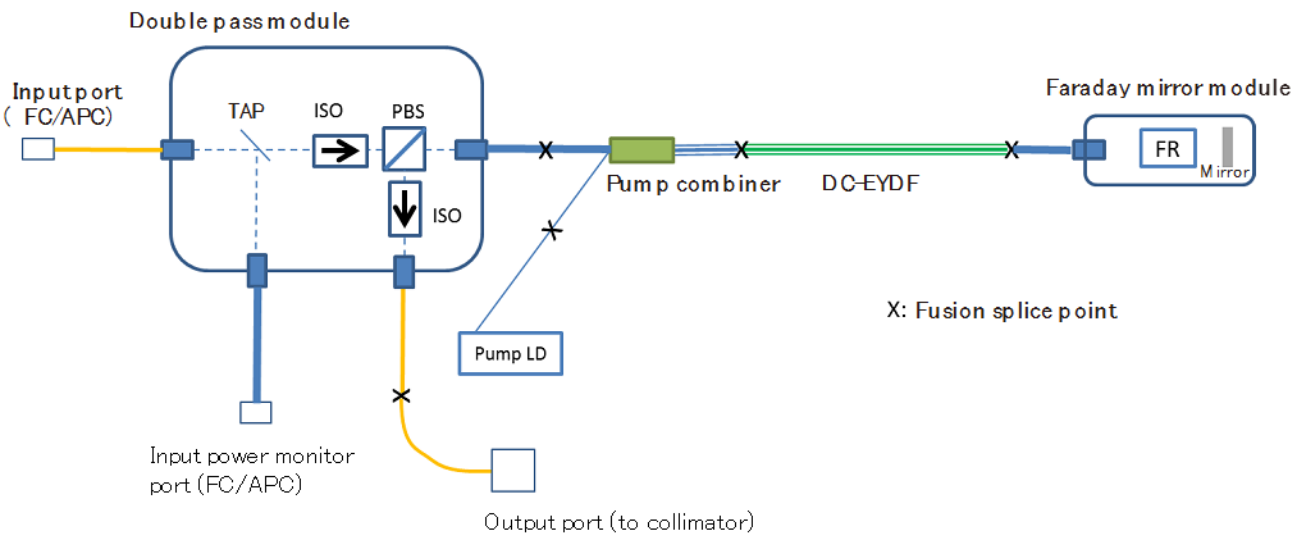
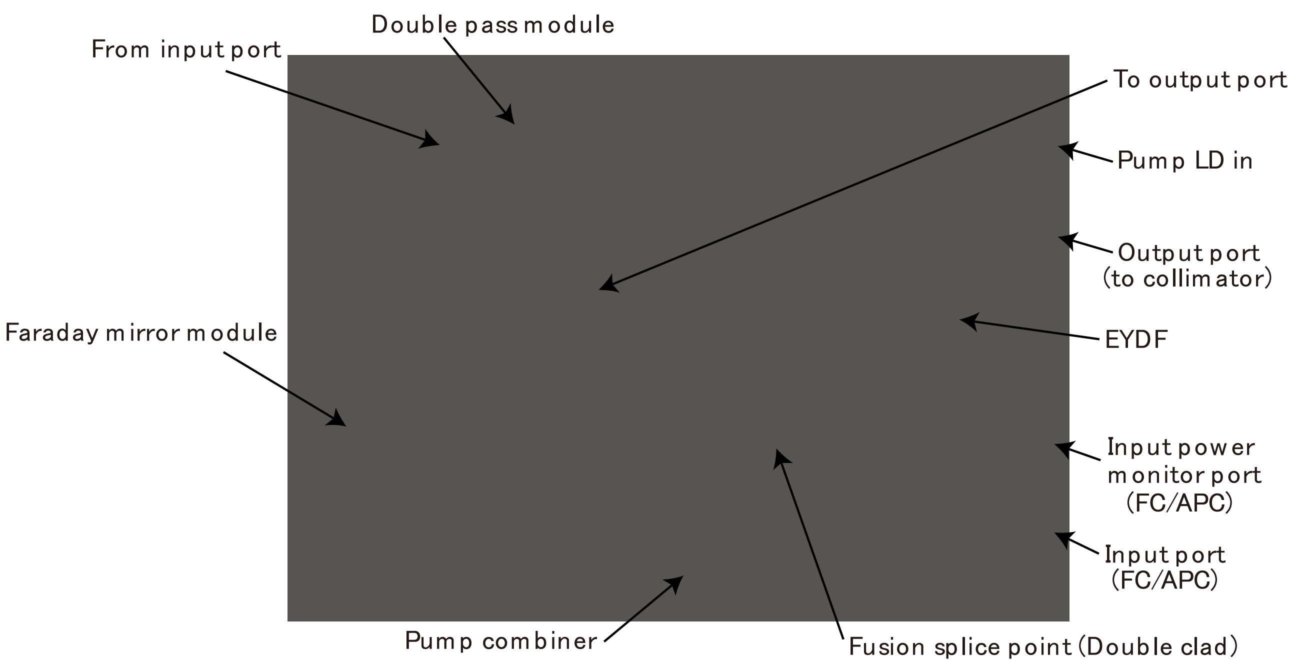
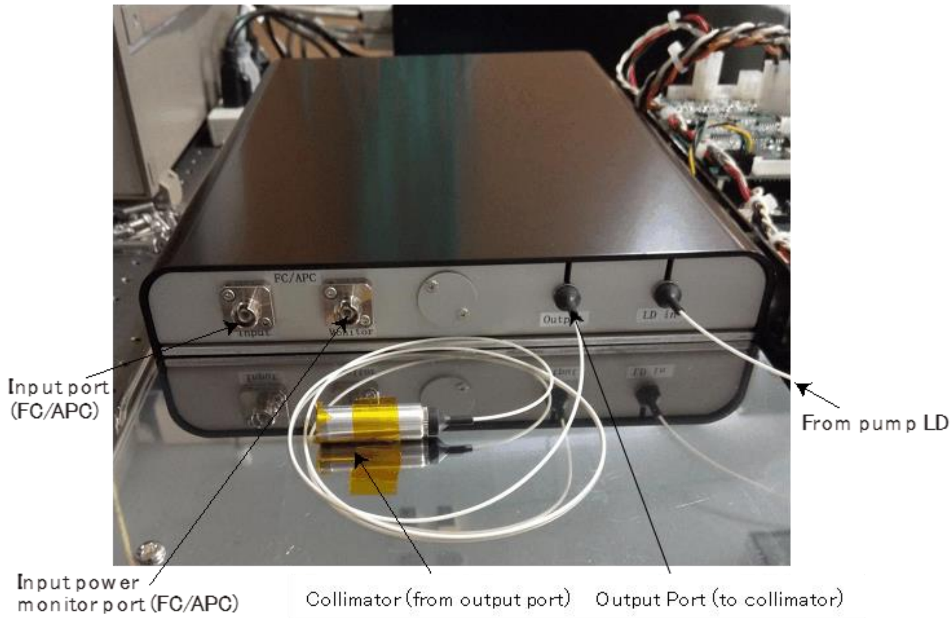


Fig. 1. Block diagram of the DP-DC-EYDFA.



(a)



(b)

Fig. 2. The fabricated DP-DC-EYDFA: (a) inside and (b) outside.

3. EXPERIMENTAL EVALUATION METHODS

Figures 3 and 4 show a block diagram and an external view of the experimental setup, respectively. As the unit under test (UUT), the DP-DC-EYDFA was evaluated by using following setup. Seed light was generated by a tunable laser source and then amplified by a 200-mW class first stage PM-EDFA. In the experimental evaluation, the input and output connectors of the UUT shown in Fig. 3 were equivalent to the input and output ports of the DP-DC-EYDFA shown in Fig. 1. Collimated output power was divided by using a TAP mirror. Specifically, 97.1% of output power was injected into an optical power meter, with the remaining 2.9% of output power being coupled to SMF and then injected into an optical spectrum analyzer.

As OHPAs for space optical communication, in addition to their excellent output and efficiency characteristics from the standpoints of high power output and low power consumption, the measurement of PER becomes important since we utilize both wavelength and polarization for the separation of transmitted light and received light. In the evaluation of high-power operation, the output light power and spectrum when the excitation light power was changed from 2.5 W to 23.6 W at wavelengths of 1540, 1550, and 1560 nm using the 5.5 m EYDF were measured by the power meter and the optical spectrum analyzer. We also monitored the temperature of EYDF during operation. In contrast, in the evaluation of PER, the PER of collimator output was measured with weakly excited (pumping power: 138 mW) EYDF at the wavelength of 1560 nm.

In order to compare with the usual SP type as shown in Fig. 5, we also cut the fiber at the input part of the FM module and directly connected it to the collimator to make an output port as a SP type EYDFA. Since the optimum EYDF length differs between the SP type and the DP type, the length was modified from 2.5 m to 7.5 m. In this measurement, the wavelength was 1560 nm, and the pumping light power was 4.7, 8.0, 11.0, and 15.7 W.

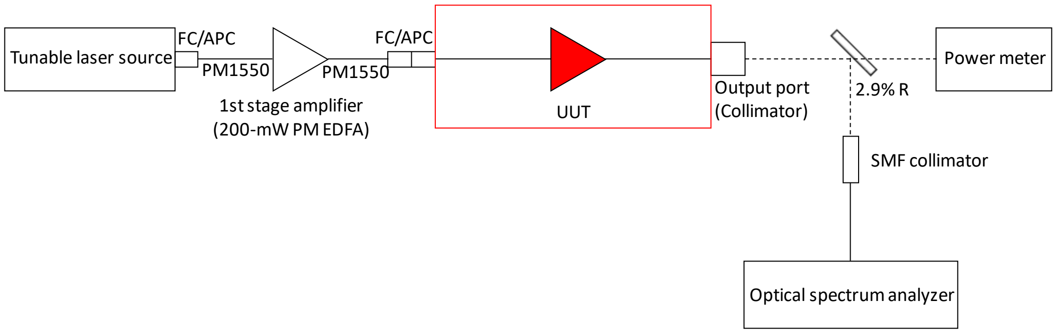


Fig. 3. Block diagram of experimental evaluation for the DP-DC-EYDFA.

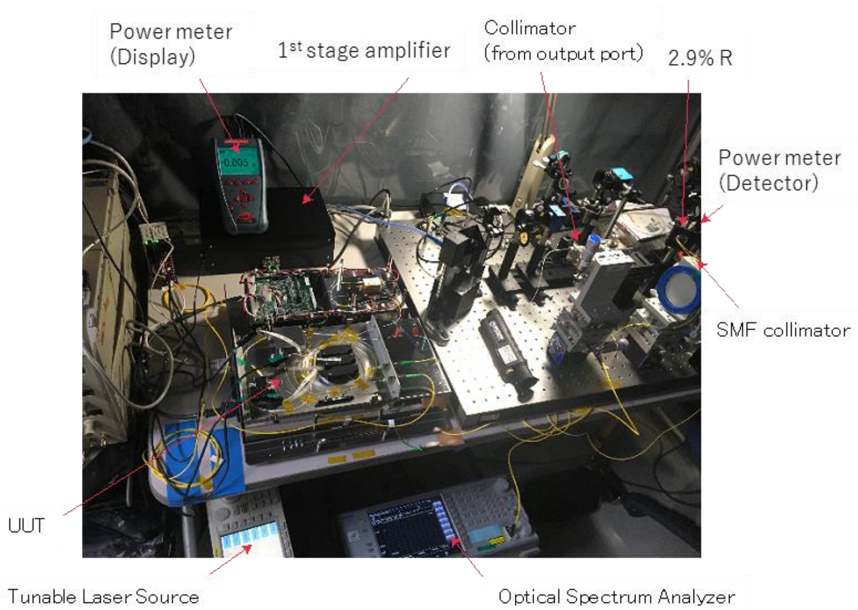


Fig. 4. Experimental evaluation system for the DP-DC-EYDFA.

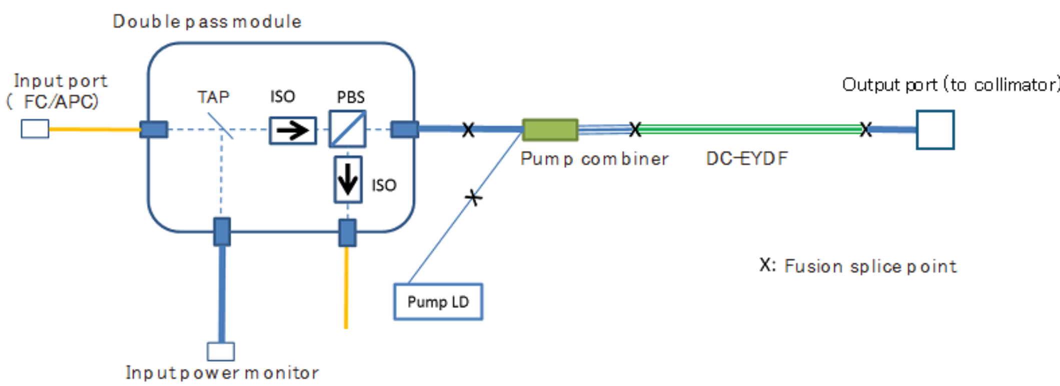


Fig. 5. Block diagram of the DC-EYDFA for SP evaluation.

4. RESULTS AND DISCUSSIONS

4.1 Measured characteristics of the fabricated DP-DC-EYDFA

Figures 6 and 7 show the measurement results of output light power (Pout) and the spectrum where the pumping light power was changed from 2.5 W to 23.6 W, respectively, with wavelengths of 1540, 1550 and 1560 nm, and EYDF of 5.5 m in length. As shown in Fig. 6, the output power at the pumping light power of 23.6 W was 7.2 W (1540 nm), 7.0 W (1550 nm), and 6.9 W (1560 nm), and thus we succeeded in high output operation of the 7-W class. Optical-to-optical conversion efficiency of up to 32.4% (1540 nm), 32.3% (1550 nm) and 32.1% (1560 nm) was achieved. As shown in Fig. 7, the amplified spontaneous emission (ASE) level was suppressed by 40 dB or more from the signal light. Moreover, the measured PER was 23.6 dB.

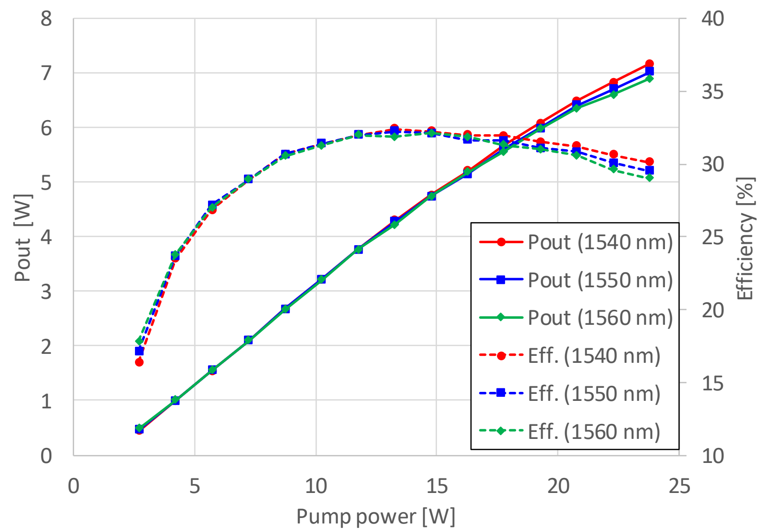


Fig. 6. Measured output power (Pout) and optical-to-optical conversion efficiency (Efficiency) of the fabricated DP-DC-EYDFA (Wavelength of input signal: 1540, 1550, and 1560 nm, EYDF length: 5.5 m).

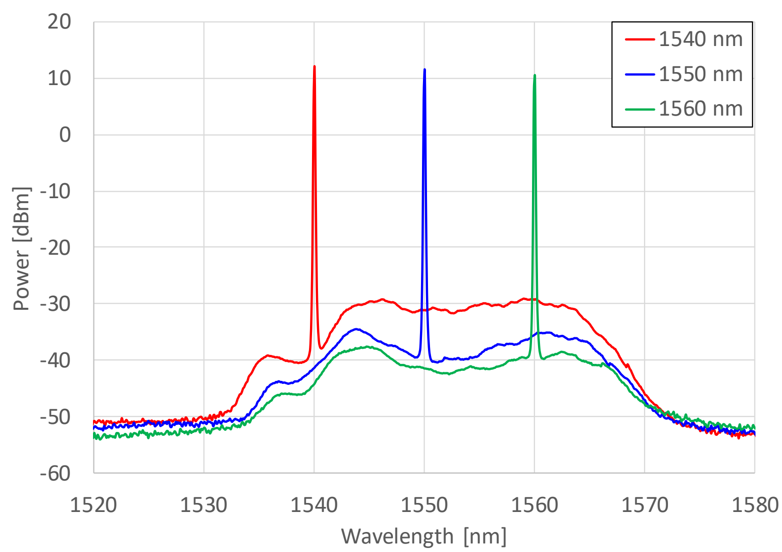
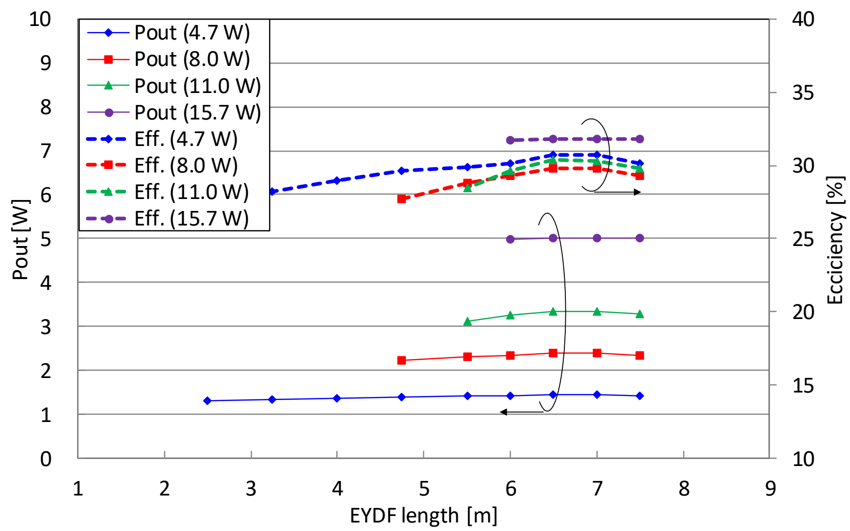


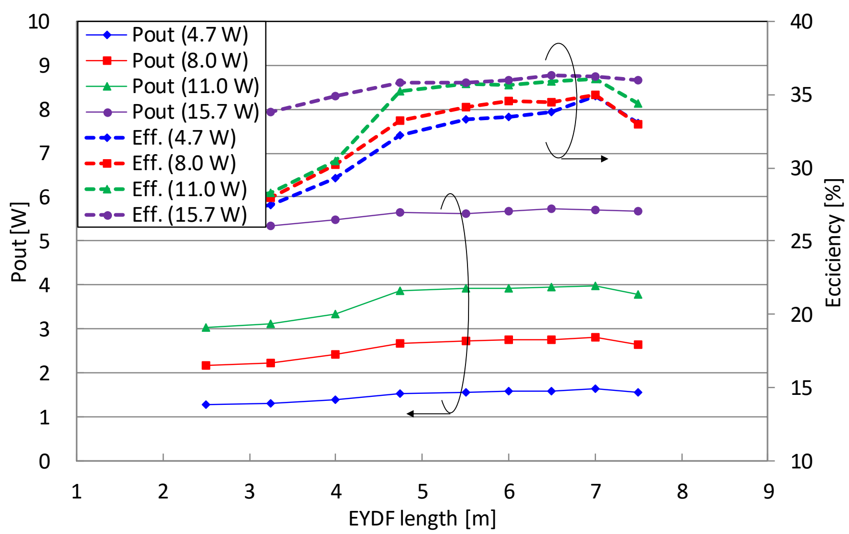
Fig. 7. Measured spectrum of the fabricated DP-DC-EYDFA between 1520 and 1580 nm (Wavelength of input signal: 1540, 1550, and 1560 nm, EYDF length: 5.5 m).

4.2 Comparison with the SP-DC-EYDFA

In Fig. 8, (a) and (b) show the measured output power and conversion efficiency of SP and those of DP, respectively. In this measurement, the EYDF length was modified between 2.5 m and 7.5 m, pumping power was 4.7, 8.0, 11.0, and 15.7 W, and the input signal's wavelength was 1560 nm. As shown in Fig. 5, in the evaluation of the SP type, since the output of DC-EYDF is directly connected to the collimator without passing through the ISO, the EYDFA was operated as forward pumping. Therefore, there was no additional loss on the output side even though it was naturally inevitable. The output power or efficiency shown in Fig. 8 (a) was then measured immediately after DC-EYDF. Conversely, in the DP type, the measured output power was lower than the output level immediately after DC-EYDF due to fusion splice loss with the pump combiner, transmission loss of the pump combiner, and transmission loss from the pump combiner side port to the output port of the DP module. In Fig. 8 (b), in order to fairly compare the SP and DP methods, the output level of the DP type was converted to that at the pump combiner output level by adding the loss of 0.52 dB regarding the DP module to the measured value.



(a)



(b)

Fig. 8. Comparison of output power (Pout) and optical-to-optical conversion efficiency (Efficiency) between(a) SP operation and (b) DP operation (Wavelength of input signal: 1560 nm, Pumping power: 4.7, 8.0, 11.0, and 15.7 W).

In Fig. 8, there are several points where the measurement result is not plotted, such as for the DP type: 2.5 m (15.7 W), SP type: 5.5 m or less (15.7 W), 4.75 m or less (11.0 W), and 4 m or less (8.0 W). These data were not obtained because parasitic oscillation occurred around 1535 nm during measurement and thus interrupted the measurement. Focusing on the results where the DC-EYDFA was stably operated, maximum output power was obtained at the EYDF length of 6.5 or 7 m in both SP and DP cases, regardless of the pumping power. At these lengths, the output power of the DP type was 1.1 to 1.2 times larger than that of the SP type. The conversion efficiency of the DP type was also 4.2 to 5.7% higher than that of the SP type. We therefore confirmed the effectiveness of the DP type. In addition, the DP type was suitable for high pumping power operation compared with the SP type. In other words, parasitic oscillation caused by an increase in amplification gain was less likely to occur in the DP type. This is due to the saturation amplification after reflection by the FM module. Therefore, we consider that the DP type is more suitable for higher output at the same input signal level.

4.3 Issues for higher output power and efficiency

As shown in Fig. 6, the output power was saturated at around 7 W and the maximum conversion efficiency was around 32% in this evaluation. These results did not satisfy our target specification of output power > 10 W. For achieving even higher output power (> 10 W) or higher efficiency, the dissipating heat of EYDF, increasing the level of input signal light, and reducing transmission loss are important issues. Figure 9 shows the temperature distribution of the DP-DC-EYDFA under the condition where the EYDF length was 5.5 m, wavelength of the input signal was 1560 nm, and pumping power was 7.2 W. In this case, the maximum temperature of EYDF reached 62.3°C. As the temperature of EYDF increases linearly in proportion to the level of pumping power, the temperature was estimated to reach around 116°C when the pumping power was 23.6 W (at output power of 7 W). During the experimental evaluations, EYDF was not fixed on the bottom aluminum plate, and thus thermal conductivity was quite low. It is therefore considered that higher output power or efficiency will be possible when we fix EYDF on the bottom plate with high-thermal-conductivity adhesives. As described in the previous section, higher input power is necessary to increase the output power without generating parasitic oscillations. In order to further reduce transmission loss, an integrated DP module design including a pump combiner must be adopted. There is also an issue regarding the reliability of the FM module due to high power operation

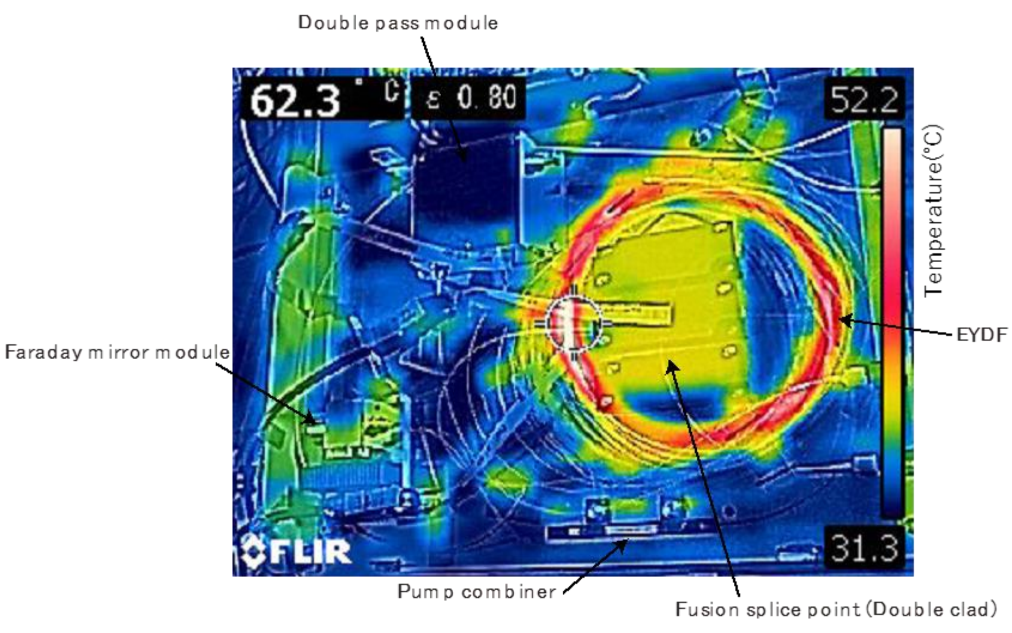


Fig. 9. Measured temperature of the fabricated DP-DC-EYDFA during amplification operation (Wavelength of signal: 1560 nm, Pumping power: 7.2 W, EYDF length: 5.5 m).

5. CONCLUSION

This paper discussed a high-power DP-DC-EYDFA. Achieving higher electrical-to-optical conversion efficiency is one of the most significant issues in realizing optical amplifiers for future space missions. To address this problem, this research focused on a DP optical fiber amplifier. The DP amplifier consists of a DP module, a FM module, a pump combiner, a MM pump LD, and DC EYDF. To achieve high efficiency, we adopted free-space optics and an integrated design for the DP and FM modules. The DP module including a tap mirror, isolators, and a PBS had dimensions of 70×50×22.5 mm, with transmission loss of 0.65 dB (from input port to pump combiner port) and 0.52 dB (from pump combiner port to output port), respectively. In contrast, the FM module measured 40×37×18.5 mm in size and the round-trip transmission loss was 0.66 dB. An experimental evaluation of the fabricated DP-DC-EYDFA was conducted, and the results indicated that it could achieve optical-to-optical conversion efficiency exceeding 32% and output power of around 7 W at the wavelength region between 1540 and 1560 nm, which to the best of the authors' knowledge is the highest output power ever measured for a DP-DC-EYDFA. In comparing with a SP-DC-EYDFA using the same EYDF, the conversion efficiency of DP was at least 4.2% higher than that of the SP type. Moreover, the measured PER of the fabricated DP-DC-EYDFA was 23.6 dB without using PM EYDF. We therefore consider that the DP-DC-EYDFA will offer a good solution for future high-power and high-efficiency optical amplifiers. In order to achieve much higher output power and efficiency, the heat dissipation of EYDF, suppression of parasitic oscillation, reduction of transmission loss, and enhancement of reliability are the subjects of our future work.

REFERENCES

[1] Araki, T., “A study of the future optical data relay system; requirements, problems and solution,” Proc. of 2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2017.
[2] Sato, Y. et al., “Current status of Japanese optical data relay system (JDRS),” Proc. of IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2017.
[3] Engin, D. et al., “Highly efficient and athermal 1550nm-fiber-MOPA based highly power down link laser transmitter for deep space communication,” Proc. of SPIE 86100G, 2013.
[4] “LGS Innovations develops modem for NASA satellite communications,” http://optics.org/news/9/1/30.
[5] https://www.nuphoton.com/shop/radh-edfa/
[6] Kehayas, E. et al., “Space qualification of multi-channel optical fiber amplifier for low Earth orbit satellite-to-ground direct downlinks,” Proc. of Free-Space Laser Communication and Atmospheric Propagation XXX, Proc. of SPIE 105240Z, 2018.
[7] Haddad, E. et al., “Comparison of gamma radiation effect on erbium doped fiber amplifiers,” Proc. of International Conference of Space Optics (ICSO), 2016.
[8] Povlsen, J. H. et al., “Optimizing gain and noise performance of EDFAs with insertion of a filter or an isolator,” Proc. of SPIE Conference on Fiber Laser Sources and Amplifiers, Vol. 1581, pp. 107-113, 1991.
[9] Georges, T. et al., “Pair-induced quenching in erbium-doped silicate fibers,” Proc. of OAA 1991, WD3, pp. 52-55, 1991.
[10] Nishi, S. et al., “Highly efficient configuration of erbium-doped fibre amplifiers,” Proc. of ECOC 1990, pp. 99-102, 1990.
[11] Giles, C. R. et al., “Gain enhancement in reflected-pump erbium-doped fiber amplifiers,” Proc. of OAA 1991, ThD2. pp. 148-151, 1991.
[12] Lauridsen, V. et al., “Gain and noise performance of fibre amplifiers operating in new pump configurations,” Electron. Lett., Vol. 27, pp. 327-329, 1991.
[13] Hakimi, F. et. al., “High power single-polarization EDFA with wavelength multiplexed pump,” CLEO'98 CWK1, 1998.
[14] Yarnal, T. M. et al., “Single polarization cladding pumped optical amplifier without polarization-maintaining gain fiber,” IEEE Photonics Technology Lett., Vol. 21-18, pp. 1326-1328, 2009.

[15] Kobayashi, Y et al., "Effects of Ge co-doping on P-related radiation-induced absorption in Er/Yb-doped optical fibers for space application," IEEE Journal of Lightwave Technologies, Vol. 36, Issue 13, pp. 2723-2729, 2018.