Development of High-Power Optical Amplifier

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ABSTRACT With the development of the D-WDM (Dense Wavelength Division-Multiplex) transmission technology together with its practical applications in recent years, optical amplifiers --in particular EDFA (Erbium-Doped Fiber Amplifier)-- used in these transmission systems are required to have ever higher performance. In this report, a high-power EDFA is presented which has achieved a high signal output of 1.5 W. The EDFA uses a set of high power pumping light sources in which the outputs of semiconductor laser diodes in the 1480-nm range are multiplexed over three wavelengths.

1. INTRODUCTION

With the development of the D-WDM transmission technology together with its practical applications in recent years, optical amplifiers --in particular the EDFA which is finding wide applications- used in these transmission systems are required to have higher power. This is because, as the total power of optical signal increases due to the increase in multiplexing signals, so does the power of the EDFA necessary to obtain the same level of optical gain. Apart from this application, high-power EDFAs have such applications as repeater-less transmission system [1], inter-satellite optical links [2], and optical signal processing which uses nonlinear effects in the fiber [3].

The realization of high-power EDFAs of the watt class may be classified into two broad categories according to the pumping wavelength used: the 980-nm range or the 1480-nm range. The former is characterized by a narrow absorption bandwidth, corresponding to the excited-state energy levels of Er ion, of 16 nm in FWHM (Full Width at Half Maximum) centering at 978 nm. Furthermore, the quantum conversion efficiency from pumping light to signal light is low with around 60% because of the large difference in the energy levels between the pumping wavelength and the signal wavelength spanning the 1530-1580 nm range. Higher power in pumping light sources is therefore needed to compensate for the low efficiency.

EDF (Erbium Doped Fiber) co-doped with Yb (Ytterbium) is used to solve this problem. Yb co-doping enables indirect stimulation of Er ions by the interaction between the ions, since Yb ion has a broader absorption range spanning 800-1100 nm in which energy transfer takes place from excited Yb ions to Er ions. The broader range of pumping wavelength permits the use of Nd-YAG lasers [5] of high-power at 1064 nm for example --which is pumped by GaAs semiconductor lasers at 800 nm-- as a pumping light source, thereby compensating for the low quantum conversion efficiency. What is more, intensive research [6] is going on to obtain higher outputs, in which high-power semiconductor lasers [4] at 980 nm in multi-mode are employed to pump a double-clad fiber. The fiber has a core co-doped with Er and Yb together with the first- and second-clad layers, such that the first clad supports the propagation of the pumping light in multi-mode, while the core the propagation of the signal light in single-mode.

On the other hand, the use of pumping lights in the 1480-nm range presents the following advantages. (1) A high quantum conversion efficiency of as high as 90% is obtained since the pumping wavelength is close to the signal wavelength. (2) A broad pumping wavelength range of 50 nm between 1450-1500 nm is available, permitting wavelength multiplexing of pumping lights. The disadvantage is that their noise characteristics are inferior to those using 980-nm pumping because a satisfactory population inversion is difficult to be generated due to the stimulated emission of Er ions in the 1480-nm range. It is possible to overcome this problem, however, by constructing a two-staged EDFA in which a preamplifier with an EDFA of 980-nm pumping is used [7].

Methods of upgrading the output power of pumping light sources in the 1480-nm range are known to include those of wavelength-multiplexing and polarization-multiplexing [8] of the 1480-nm semiconductor lasers. Moreover, a cascaded Raman laser [9] has been recently reported which incorporates Raman amplification with a fiber laser. The authors have been carrying out research and development of high-power EDFAs which use the 1480-nm semiconductor lasers as pumping light source, and have recently succeeded in developing a high-power EDFA of 1.5 W signal output power. In this report, upgrading technologies of EDFAs which use the 1480-nm semiconductor lasers as pumping light source will be presented.

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2. CHARACTERISTICS OF 1480-NM SEMICONDUCTOR LASER FOR PUMPING

In order to realize high-power EDFAs, the authors are investigating the technology of high-power injection in which pumping lights are combined by wavelength multiplexing prior to injection into EDFs. While ordinary semiconductor lasers in the 1480-nm range have a center wavelength located between 1460 nm and 1490 nm, they conventionally have a wide output spectrum of around 5 nm FWHM since they oscillate in a Fabry-Perot mode. This wide output spectrum leads to imposing limitations on the wavelength spacing at wavelength multiplexing. In terms of loss also, if the output spectrum of the pumping light is wider than the transmission spectrum of the wavelength-multiplexing device, the loss in effective pumping power will become significant. Furthermore, the combining efficiency disadvantageously depends on the driving current of the laser since the current causes shifts in the center frequency.

In an effort to solve these problems, the authors have developed a semiconductor laser module, in which an FBG (Fiber Bragg Grating) is used as external cavity to stabilize the output wavelength [12]. Figure 1 shows a schematic of the module. The output of the laser is coupled into a pigtail fiber through collimating lens and focusing lens. Polarization maintaining fiber was selected as the pigtail fiber for the purpose of polarization combining of laser outputs. The FBG used for the developed laser module measures 50 mm in length and 2.7 mm in diameter, and is placed 700 mm to 800 mm apart from the module.

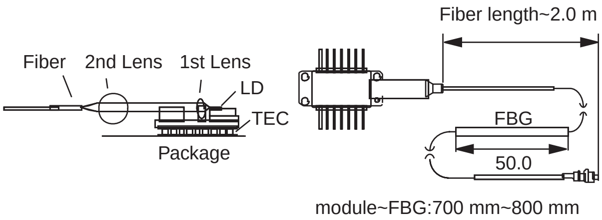

Figure 1 Schematic of stabilized laser diode module

Figure 2 shows the output vs. driving current characteristics together with the output spectrum of the module driven at a sub-mount temperature of 25°C. Data for both the laser modules with (Fig.2 (b)) and without (Fig.2 (a)) FBG for wavelength stabilization are shown for comparison. The driving current characteristics in the upper half of Figure 2 shows that the output has no kinks, irrespective of being with or without FBG, up to 800 mA in driving current; that an output power of 160 mW is obtained at a driving current of 600 mA; and that the insertion of FBG reduces outputs only slightly. The lower half of Figure 2 gives the results of output spectrum measurement at a driving current of 500 mA, showing that the output spectrum has successfully been reduced from 5 nm to 1.5 nm FWHM with the developed laser module due to the use of the FBG.

Figure 3 shows the measured results of the driving current dependence of center wavelength. The center wavelength of the developed laser module has a small dependence on the driving current, so that more stabilized characteristics in output combining are expected to come compared to conventional laser modules in which no FBG is used.

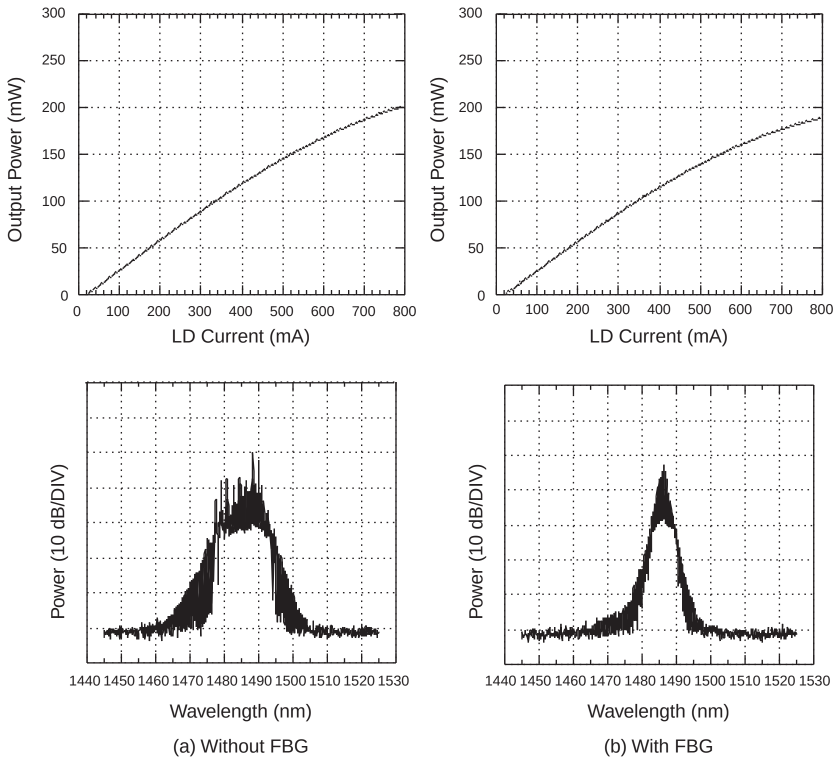

Figure 2 Comparison of IL characteristics and output spectra of laser modules

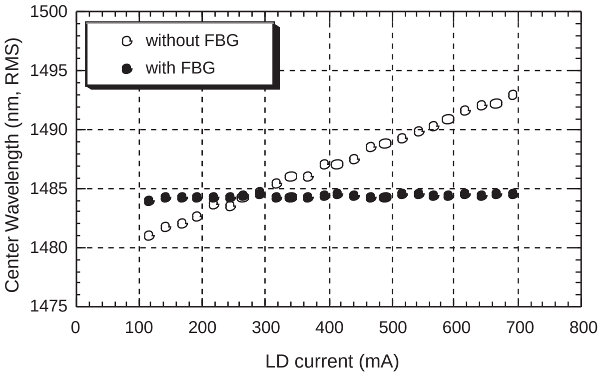

Figure 3 Driving current dependence of center wavelength

3. STRUCTURE AND CHARACTERISTICS OF HIGH-POWER OPTICAL FIBER AMPLIFIER

The developed EDFA uses semiconductor lasers described above, in which the FBG is employed to stabilize the wavelength. EDFAs of bi-directional pumping are cascaded to constitute a two-stage configuration, as shown in Figure 4.

The pumping lights were combined first by polarization combining the outputs from polarization maintaining fibers using PBC (Polarization Beam Combiner), and subsequently by wavelength multiplexing using the two-channel and three-channel WDM couplers for the first-stage and second-stage EDFAs respectively. In all, 20 laser modules were used. The center wavelengths of pumping lasers were 1465 nm and 1490 nm for the two-channel combination, and 1463 nm, 1478 nm, and 1493 nm for the three-channel combination. The pumping light power into the EDF was 880 mW at the three-channel combination in which six laser modules were used. To deal with this high power, the FC connector with an angled end face was used at the output port of EDFA, and an optical isolator was inserted into the midpoint of EDFs, thereby suppressing oscillation due to multiple reflections. The measurement method for the output was such that a calorimeter was used for power measurement, and an optical spectrum analyzer was used for simultaneous measurement of the output spectrum branched through an 18-dB coupler.

The optimization of EDF is another important element in design technology. In this development, an EDF was designed to maximize its amplification efficiency at 1480-nm pumping, and a new EDF with a numerical aperture (NA) of 0.23 and a core diameter of 5.5 µm has been developed. In terms of conversion efficiency from pumping light to signal light using this EDF, a single-stage EDFA with 1480-nm pumping has achieved a quantum conversion efficiency of 91% and a power conversion efficiency of 86%.

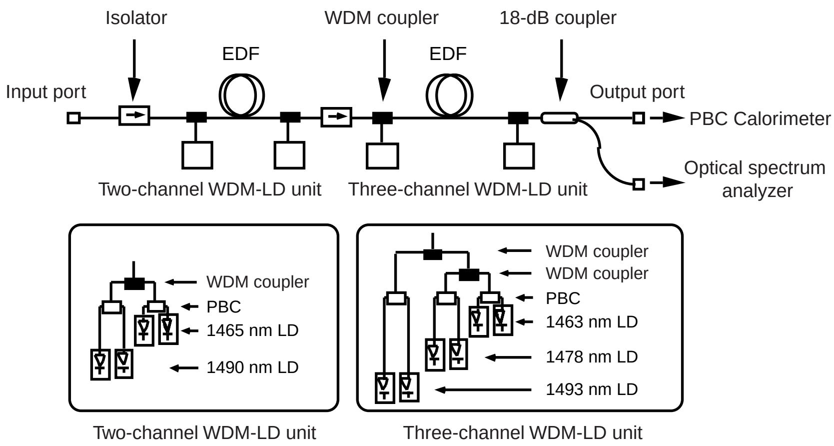

Figure 4 Schematic diagram of high-power EDFA

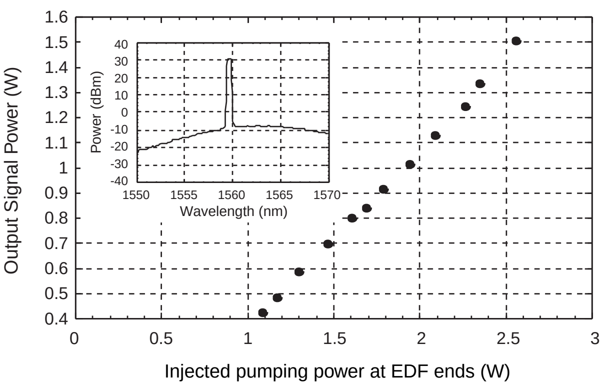

Figure 5 Output characteristics of high-power EDFA

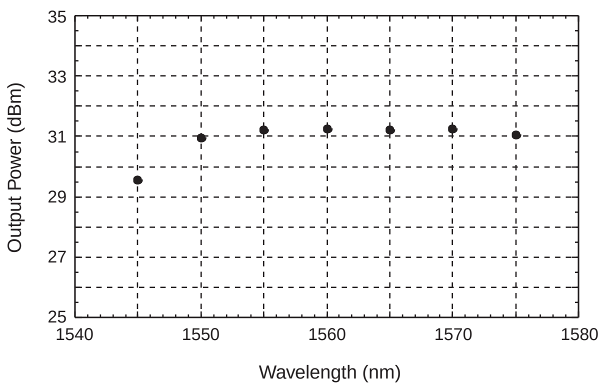

Figure 6 Wavelength dependence of the output power

The length of the EDF was also optimized to have a maximum output, and it was found that the optimum lengths for the first-stage and second-stage EDFAs were 93 m and 34 m respectively. Figure 5 shows the output characteristics of the EDFA vs. pumping power injected at the EDF ends together with the output spectrum. The input optical signal is 1560 nm in wavelength and +7.2 dBm in power. The ratio of optical signal power to total optical output power was calculated as 0.99 or more --a high value, indicating that the EDFA was operating at a highly saturated state. The power of the optical signal output was found to increase linearly in proportion to the increase of the pumping light power, and 1.5 W was attained at a pumping light power of 2.56 W. The power conversion efficiency was 59% --from the pumping light to the signal light measured at the input and output ports of the EDFA-- and the slope efficiency 72%. Compared with the single-stage configuration, the developed EDFA has a lower power conversion efficiency. This is mainly due to the insertion loss of the optical devices inserted at the midpoint between the EDFAs, in addition to the fact that --since conversion efficiency depends on the wavelength of the pumping light-- the conversion efficiency is lower in the near 1465-nm range than in the 1480-nm range. Figure 6 shows the wavelength dependence of the signal light power at an input signal power of -3 dBm. It is seen that a signal light power of 1 W (30 dBm) is obtained in a bandwidth of 30 nm at least, with its peak at 1560 nm.

4. TASKS FOR THE FUTURE

We will briefly discuss the importance of both high-power pumping lasers and the wavelength multiplexing technology of pumping light, which are necessary to realize high output powers of several watts with the EDFAs pumped in the 1480-nm range.

4.1 High-Power Pumping Laser

It is difficult to upgrade the conversion efficiency with the EDF, which is approaching the theoretical limits. High-power laser modules are therefore needed to obtain higher output powers. At present, modules with wavelength stabilized semiconductor lasers having an output power of 180 mW --fiber output-- at a driving current of 600 mA are commercially available. To have higher outputs in the future, the present technology has to be examined in terms of the cooling efficiency of the laser module and the reliability assurance at large current driving.

4.2 Wavelength Multiplexing Technology of Pumping Light

So far, WDM couplers based on dielectric filters have been used as wavelength multiplexing device. With this type of WDM couplers, however, the required number of couplers increases as the number of multiplexing increases --two or more WDM couplers are required for multiplexing three or more waves. The loss of pumping light before being injected into EDF will become significant, and the greater the number of multiplexing, the larger the loss will be. What is more, from the standpoint of downsizing EDFAs, it is desirable to use an optical circuit which includes fewer fiber joints enabling circuit integration. In an effort to develop a new device, the authors are investigating the application of PLC (Planar Lightwave Circuit) formed on silica substrates, which allows higher degree of multiplexing of pumping lights while maintaining small combining losses. A prototype of the PLC device has been fabricated, which combines eight waves by wavelength multiplexing using Mach-Zehnder interferometers[13].

Figure 7 shows the schematic diagram of the new PLC device. The device aims to combine eight outputs of wavelength stabilized pumping lasers so as to obtain a pumping output spanning from 1450 nm to 1502.5 nm with 7.5-nm spacing. The difference in relative refractive index of TiO_2-doped waveguide is 0.4%, and the dimensions are 3.4 mm in width, 74.0 mm in length, and 2.0 mm in height. Figure 8 shows an appearance of the wavelength multiplexing device based on the Mach-Zehnder interferometer. Figure 9 gives the transmission spectrum showing a minimum insertion loss of 0.9 dB for every port. The effective combining loss of pumping power due to the transmission wavelength limitation at each port was found to be 1.2 dB or less.

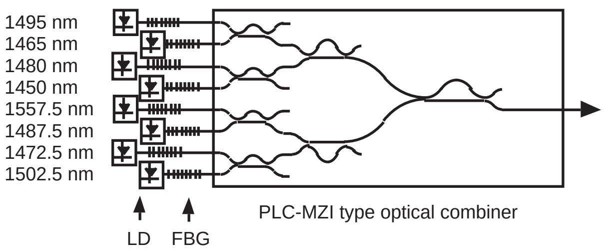

Figure 7 Schematic diagram of PLC Mach-Zehnder interferometric wavelength multiplexer

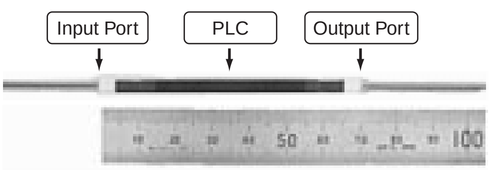

Figure 8 Appearance of PLC wavelength multiplexer

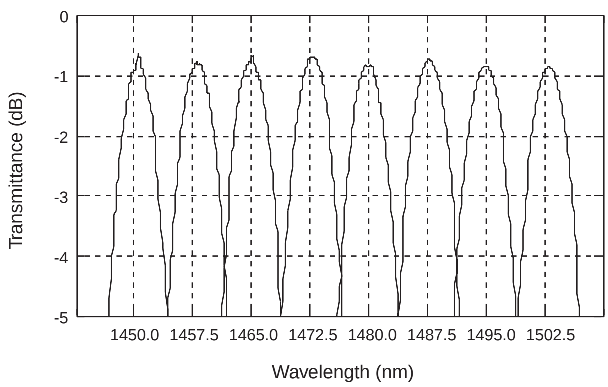

Figure 9 Transmission spectrum of PLC Mach-Zehnder interferometric multiplexer

5. CONCLUSIONS

A high-power fiber-optic amplifier with an output of 1.5 W has been developed based on the pumping technology which combines 1480-nm semiconductor lasers through wavelength multiplexing. The amplifier has achieved an output of 1 W or greater at a wavelength bandwidth of over 30 nm, thus demonstrating improvements in the number of waves to be multiplexed together with the combining efficiency of pumping lights based on the use of wavelength stabilized 1480-nm pumping lasers. Furthermore, a prototype PLC combiner based on Mach-Zehnder interferometer has been fabricated, which is expected to improve the efficiency in wavelength multiplexing. In the future, we plan to develop pumping units and high-power fiber-optic amplifiers using the PLC technology based on the Mach-Zehnder interferometer.

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