Demonstration of Broadband Raman Amplifiers: a Promising Application of High-power Pumping Unit

by Yoshihiro Emori * and Shu Namiki *

ABSTRACT A high-power pumping unit with a total optical output power of 2.2 W has been developed by connecting a fiber Bragg grating to a pumping laser diode, constricting and stabilizing the lasing wavelength, and performing wavelength-division multiplexing for 12 wavelength channels between 1405 and 1510 nm, with a Mach-Zehnder interferometer made with silica-based planar lightwave circuitry. Using this pumping unit, Raman amplification tests were carried out using three types of transmission link fibers --25-km single mode fiber (SMF), 25-km dispersion shifted fiber (DSF) and 20-km reverse dispersion fiber (RDF)-- as the Raman amplification medium. At an average gain of 2 dB for SMF and 6.5 dB for DSF and RDF, amplification characteristics of ±0.5 dB gain deviation over a 1520- to 1620-nm band were achieved.

1. INTRODUCTION

At the beginning of the 1990s, the development of erbium-doped fiber amplifier (EDFA) technology brought to optical communications systems a dramatic leap in transmission capacity as well as in electrical repeater spacing. However the explosive growth in the Internet, which began in North America at about the same period, increased the volume of public telecommunications traffic to the point where even greater capacity was required. Luckily the gain band of EDFAs is comparatively wide, so that wavelength division multiplexing (WDM) using all the optical signals included in this wavelength band was identified as a method that could provide a solution to the problem, and was rapidly implemented. The greater part of the information available on the Internet still consists of still pictures, the importance of video images is expected to increase so that there will be no slackening in demand for transmission capacity.

WDM technology using EDFAs started from 1550 nm, where gain flattening is easily accomplished, but in only a few years spread to the 1530-nm band and has recently been employed even in the 1580-nm band, where the small gain coefficient had made it impracticable. The band of low fiber loss, however, is wider than the band in which amplification by EDFA is possible, so that interest in optical amplifiers that operate outside the EDFA bandwidth is increasing. One likely candidate is the Raman amplifier. In optical amplifiers using erbium or other rare earth ions as the medium, the gain wavelength band is determined by the energy level of the ions, whereas in Raman amplifiers it is determined by the wavelength of the pumping light. [1)–3)] This makes it possible to amplify any desired wavelength simply by selecting the appropriate pumping wavelength.

The principle of Raman amplification in optical fibers was confirmed by Stolen et al., [4)] and verified by experiments carried out by Aoki et al. [5)] It was applied by Mollenauer et al. [6)] in optical soliton transmission, and Edagawa et al. verified WDM transmission using laser diodes as the pumping source. [7)] At the time, however, obtaining sufficient gain required several hundred milliwatts of pumping power, and there was no alternative to solid-state lasers. Thus in telecommunications applications priority was given to EDFAs, which would operate perfectly well on a few tens of milliwatts. Highly efficient EDFAs, pumped by laser diodes, came into wide use, while Raman amplifiers were left on the sidelines.

Research on Raman amplifiers continued, however, and two broad advantages were identified. The first was that when a Raman amplifier was structured as a distributed type, noise levels for the system as a whole could be reduced compared to amplifiers using fibers doped with rare earth ions, which signals are subjected to lumped amplification in the transmission link. [8)] The second advantage was that by broadening the bandwidth of the pump using WDM, the gain bandwidth could be broadened in a way not achievable with EDFAs. [9), 10)]

This paper describes the development of a broadband HPU using WDM technology with a laser diode, and reports on a Raman amplifier using this unit that achieved extremely broadband amplification characteristics, with a gain deviation of ±0.5 dB at wavelengths from 1520 to 1620 nm.

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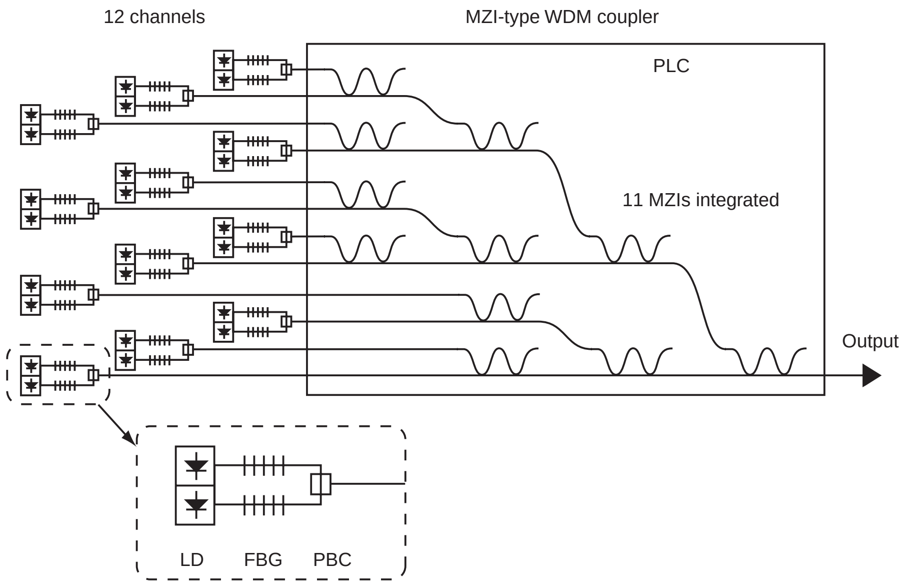

Figure 1 Schematic diagram of 12-channel HPU for WDM

2. BROADBAND HIGH-POWER PUMPING UNIT

The popularity of high-output EDFAs has been greatly accelerated by the realization of compact pumping laser modules based on compound semiconductors. [11] Since a larger number of channels requires higher laser power, the development of EDFAs for WDM has led to advances in techniques for increasing pumping laser output. This increase has been particularly evident in 1480-nm lasers, and outputs as high as 250 mW at the end of an SMF have already been reached. [12]

To reach the higher outputs that are essential if EDFAs are to be practicable for broadband WDM transmission, efficient coupling of the pumping sources must be achieved. In recent years a high-power EDFA has been developed that multiplexes three polarization multiplexed wavelengths (for a total of six), for an signal light output of 1.5 W. [13] The absorption band of an erbium-doped fiber (EDF) in the 1480-nm band is from 1450 to 1500 nm, and to multiplex three or more wavelengths, the lasing spectrum of each pumping laser must be constricted and stabilized. This can be achieved during the module fabrication process by forming a fiber Bragg grating (FBG) on the fiber pigtail to provide an external cavity mirror having narrow-band reflection characteristics. [14]

By using an FBG to narrow and stabilize the lasing spectrum of the pump laser diode to a few nanometers, it was possible to get efficient combining using a Mach-Zehnder WDM coupler. Thus Tanaka et al. were able to produce an 8-wavelength integrated WDM coupler using silica-based planer lightwave circuit (PLC) technology, thereby developing an inexpensive and efficient coupler for a high-density WDM pumping unit. [15] This made it possible to realize a high-power pumping unit (HPU), with an output exceeding 1 W.

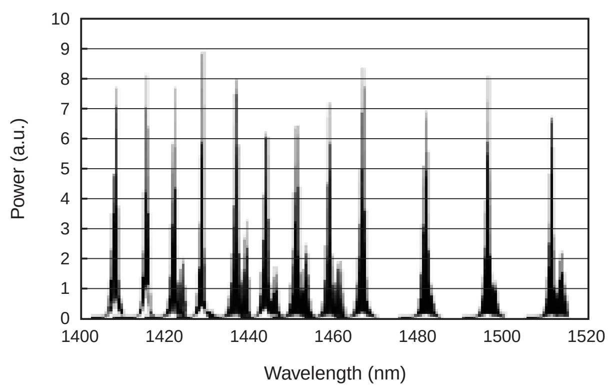

Figure 2 Output spectrum of HPU

3. RAMAN AMPLIFIER WITH FLAT-GAIN BANDWIDTH OF 100 NM

The 1480-nm WDM pumping unit developed in order to increase EDFA output can be readily adapted for broadband Raman amplifiers. In Raman amplification, around the 1500-nm band, gain is produced at approximately 110 nm on the long-wavelength side, so that if the pumping unit is multiplexed around 1450 nm to have a broad bandwidth, Raman amplification also occurs in a broad band around 1560 nm. If the signal light and the pumping light are multiplexed/demultiplexed using a WDM coupler, the approximately 100-nm wavelength difference between the pumping light and the signal light will be the upper limit of the bandwidth of Raman gain. Recently the authors have multiplexed the pumping light over a 105-nm bandwidth and have achieved broadband gain of 100 nm. [16]

Figure 1 shows the optics of a prototype 12-channel WDM laser diode unit. Each channel is polarization multiplexed by a polarization beam combiner (PBC) laser diode stabilized by an FBG. The multiplexer/demultiplexer is a silica-based PLC, with 11 Mach-Zehnder interferometers integrated on a single substrate. Polarization multiplexing of the laser diode is designed to increase pumping unit output, as well as to suppress the polarization dependence of Raman gain. Figure 2 shows the HPU output spectrum, and Figure 3 shows total output power (the I-L characteristic). At a drive current of 700 mA per diode, total output was 2.2 W. Channel spacing was approximately 7.5 nm from 1405-1457.5 nm, and approximately 15 nm from 1465-1510 nm. The reason for this asymmetrical channel assignment is to provide asymmetrical compensation for the gain conditions resulting from the fact that short-wavelength pumping light causes Raman amplification of long-wavelength pumping light. Figure 4 shows the experimental setup.

Coupling of the pumping light and the signal light was accomplished by a counter-propagating configuration using a long-wavelength pass filter (LWPF). Total insertion loss for two isolators and the LWPF was 1.6 dB at 1550 nm. Measurements of gain conditions were basically carried out using a broadband amplified spontaneous emission (ASE) light source, but for confirmation purposes, measurements were also made using probe light input in addition to the ASE source using a tunable laser. Figure 5 shows the net gain profiles for Raman amplifiers of extra-broad bandwidth using three types of fiber--SMF, DSF and RDF. [17)]

By adjusting the pumping power for each channel it was possible to obtain flat gain over a wide bandwidth, with a gain deviation of only ±0.5 dB across a bandwidth of 100 nm. Average gain was 2 dB for the 25-km SMF, and 6.5 dB for the 25-km DSF and 20-km RDF. Gain in Figure 5 includes fiber loss, and is the gain defined by the ratio of input to output signals. The transmission loss was approximately 5 dB for each of the fibers.

Figure 6 shows the allocation of launched pumping power for Raman amplifiers with gain flattened over 100-nm bandwidth. As can be seen, due to the Raman effect between pumps, launched power at short wavelengths has to be made greater than at long wavelengths to keep gain flat. Although SMF had the largest total pumping power, average gain was less than for the other two types, so that its gain efficiency was lowest of all. RDF and DSF had the same average gain, but since the pumping power required was 790 mW for DSF but only 610 mW for RDF, we see that RDF was more efficient. This can largely be explained by the fact that Raman gain is proportional to pumping power density, and that mode field diameter decreases in the sequence SMF, DSF, RDF.

Direct comparisons between EDFAs and distributed Raman amplifiers are complicated by the difference between the lumped and distributed types, but if the total pumping power necessary to get a bandwidth of 100 nm is 600 mW, it can be seen that Raman amplifiers cannot be dismissed as inherently less efficient than EDFAs.

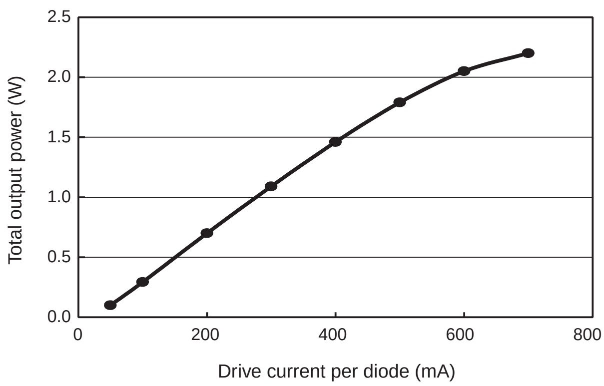

Figure 3 Total output power of HPU

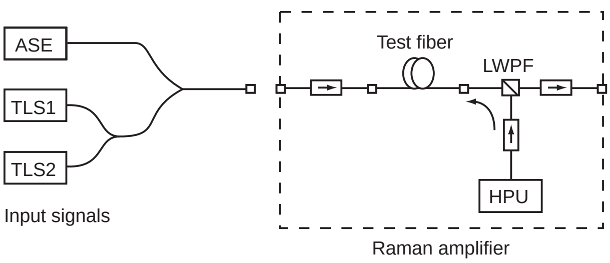

Figure 4 Experimental setup

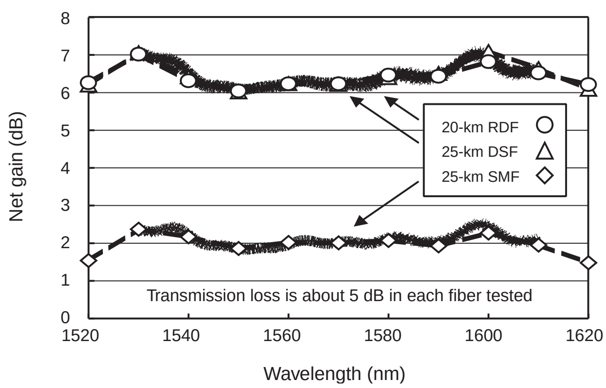

Figure 5 Net gain profiles for Raman amplifiers of 100-nm bandwidth

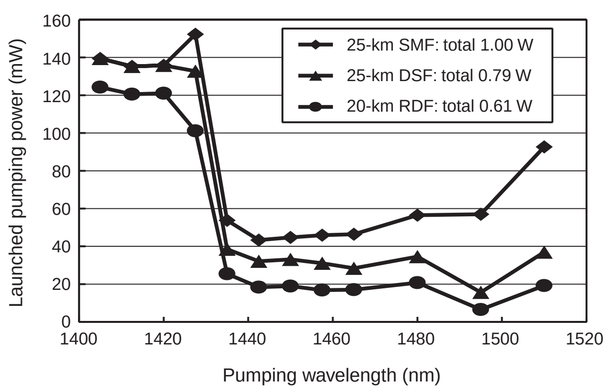

Figure 6 Allocation of launched pumping power for Raman amplifiers of 100-nm bandwidth

4. APPLICATIONS OF BROADBAND RAMAN AMPLIFIERS

Particularly with regard to WDM transmission, research is being conducted to reduce noise levels in the system as a whole through the use of distributed Raman amplifiers. In the EDFA method of repeating that was used previously, the signal light level is high and nonlinearity due to four-wave mixing in particular poses problems, so that it is difficult to achieve WDM transmission over DSF links in which the zero-dispersion wavelength is included within the signal bandwidth. If, on the other hand, Raman amplification is built into a WDM non-repeating transmission link using EDFA, it is possible to reduce the signal level in the transmission link by the amount by which the noise characteristic is improved. Research groups at NTT and Lucent have made use of this effect, reducing the signal level on DSF links, in which the zero-dispersion wavelength is in the signal band, thereby suppressing the nonlinear effect and achieving large-capacity WDM transmission.[18), 19)] The use of Raman amplification in SMF-RDF links, which are attracting attention to their dispersion-compensation properties, has also been reported to have reduced the effect of self-phase modulation on the signal.[20)] Eliminating noise and nonlinearity is a matter of life and death in large-capacity WDM transmission, and distributed Raman amplifiers are one highly promising approach to a solution.

5. CONCLUSION

Research on Raman amplifiers has a long history, and in the days when the search was on for optical amplifiers for telecommunications, they were regarded as a prime candidate. The great progress made in erbium-doped fiber amplifiers, however, rather put Raman amplifiers in the shadows. As EDFA-based WDM transmission technology has matured, however, renewed attention is being paid to Raman amplifiers. As the present work has demonstrated, the fact that their gain bandwidth is determined by the pumping wavelength can be utilized to realize a gain bandwidth of 100 nm, and applications to a wide variety of systems are anticipated. A variety of configurations are also possible--lumped, distributed, or even in combination with EDFAs, so that the Raman amplifier will doubtless be indispensable in super-broadband WDM transmission over the whole optical fiber low-loss band, and in the next generation of long-haul, high bit-rate, large-capacity WDM transmission over dispersion-compensated links.

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