Hybrid Amplification Approach to Communications beyond C- and L-Bands

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Abstract: This report introduces novel techniques to amplify new bandwidths rather than C- and L-band by utilizing advantages of each amplification phenomena such as high power efficiency and flexible bandwidth to overcome each of its drawback. © 2022 The Author

1. Introduction

With the development of data centers and distribution of 5G/6G information, there is an exponentially increasing and limitless demand for trunk transmission lines. To meet this demand, high transmission rates and advanced modulation formats that increase the amount of information per bit have been introduced, but due to the limitations of the transmittable bandwidth such as C-band and L-band covered by EDFA, the capacity expansion is approaching its limit. For further capacity expansion, it is mandatory to introduce new and unused fiber bandwidth (e.g. O-, E-, S- and/or U-bands) exceeding 40THz out of 50THz transmission bandwidth of the optical fiber. Optical amplifiers that enable long-distance transmission in the unused bands have been studied for a long time, and semiconductor amplifiers (SOA), rare-earth-doped amplifiers (PDFA, BDFA, TDFA, etc.), nonlinear amplifiers such as Raman amplification and parametric amplification, etc. have been extensively studied [1-6]. Each amplification methods has its advantage, however, it has also its drawbacks, such as limited and fixed bandwidth, extremely poor power conversion efficiency from pump to signals, or insufficient total output power. Thus none of them could be a single solution like an EDFA.

Here, new techniques have been proposed that can amplify new bands rather than the C- and the L-band by multiplying the advantages of various proposed techniques to overcome each one's drawbacks.

2. Integration / combination of multiple amplification related phenomena

Table 1 shows the candidates of the integration, and their bandwidth freedom and power efficiency. The first candidate for the technology to be combined is a highly power efficient EDFA with an energy efficiency exceeding 80%. And the proposed partner of the EDFA is a parametric wavelength conversion, which has relatively high energy efficiency among nonlinear phenomena in addition to flexible wavelength bandwidth. The key to the expansion to the new bands is this wavelength conversion' bandwidth flexibility [7]. Another possible technology for the combination is Raman amplification. It also has flexibility on available bandwidth even though its power efficiency is slightly worse than other 2 technologies.

Table 1. Technologies and their characteristics

Technology	Bandwidth	Power Efficiency
EDFA	Fixed and Narrower (35nm)	Very Good
Parametric Wavelength Conversion	Flexible and Wide (~50nm)	Moderate
Raman Amplification	Flexible and Wider (~100nm)	Inefficient

3. EDFA + Parametric Wavelength Conversion

In this combination, new band signals would first be wavelength converted to C- and/or L-band for high power efficient amplification. The EDFA amplified wavelength converted idlers will be converted back again by another wavelength conversion with about ~0dB conversion efficiency. As a result, new band signals would be amplified. Figure 1 shows an actual amplification example. S-band WDM signals are wavelength converted to L-band. After amplification by L-band EDFA, they are converted back to original S-band. Since pump light with phase modulation is used for the wavelength conversion, the spectrum of the signal converted to the L-band is spectra broadened. However, as the phase noise is canceled by counter dithering when the signals are converted back to the original S-band, the degradation is disappeared in the amplified S-band signals.

By optimizing the conversion efficiency in the first wavelength conversion, the signal gain amount by EDFA, and the conversion efficiency of the second wavelength conversion, the total NF could be realized to 5.5 dB, which is equivalent to commercial EDFAs [8, 9]. And it seems to be sufficiently practicable from the result of the transmission experiment of the 8-channel 10-Gbaud 16 QAM signals [10]. As the adjustment of the conversion efficiency influences the total energy consumption and NF as a black box amplifier, an optimum solution can be obtained not to make EDFA gain saturation.

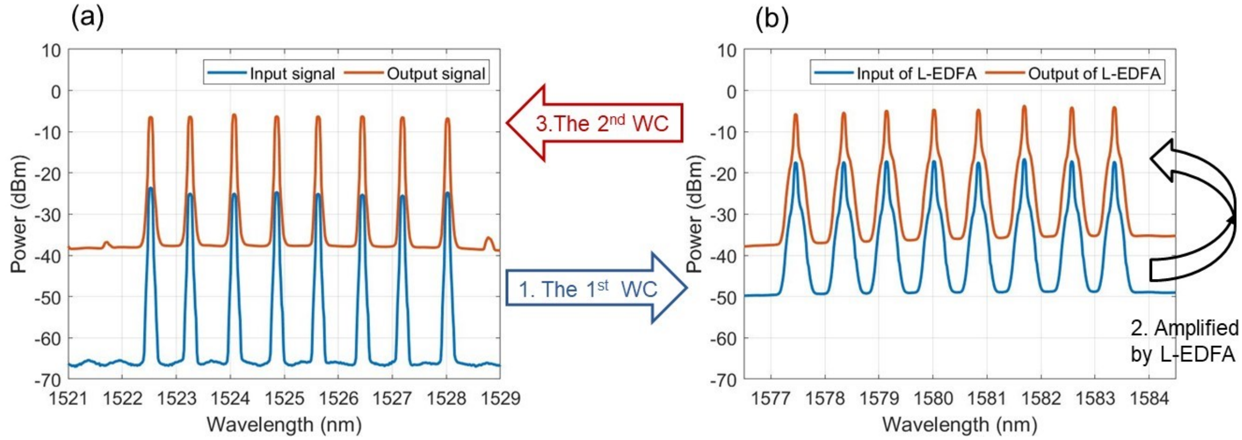

Fig. 1. (a) Input and output WDM signals of S-band amplifier, consist of 2 wavelength conversions and an L-band EDFA. (b) Input and output WDM signals of the L-band EDFA, which are broadened due to phase modulation of pump for a wavelength conversion.

In this scheme, gain bandwidth of high energy efficient EDFA should be located at the adjacent to the target bandwidth. From this restriction, the band expansion may limit to S-band (1460nm-1530nm) and/or U-band (1600nm-1650nm). To take out this restriction, the third candidate of Raman amplification in the table would be used instead of EDFA.

4. Parametric Wavelength Conversion + Raman Amplifier (Phase Sensitive Amplifier: PSA)

In the newly used bandwidth, fiber attenuation is worse compared with the conventional C-band and L-band, which are used with EDFAs. Even when the network scale is relatively small such as a short distance network or data center networks, there are no problems. However, in the case of a relatively large network scale such as metro network or a long-haul network, the transmission characteristic strongly depends on noise characteristic of new bands, and there is a possibility that the transmission characteristic in a new band is deteriorated compared with the conventional C- and L-band transmission with EDFAs.

Phase Sensitive Amplifier (PSA) is an optical parametric phenomenon same as wavelength conversion, and it is well known to realize 3dB lower noise figure than other amplification technologies. When the idler light generated by the parametric wavelength conversion, phase-sensitive amplification is possible by managing the phase relationship between the pump, the signal, and idler lights [11]. The proposed configuration is shown in Figure 2. By reducing the conversion efficiency as much as possible in the parametric wavelength conversion of the first stage, the generation of the collimated noise inhibiting the phase sensitive amplification is suppressed. Furthermore, the Raman amplification of the second stage makes the power of the pump sufficient and also the power of the idler lights equal to the signals, which is a condition of the PSA. The phase matching condition between pump/signals/idlers is satisfied by adjusting the phase of the pump light by the FBG between the first stage and the second stage. Phase sensitive amplification is performed without additional noise in the third PSA stage to obtain an enough signal net gain [12]. Fig. 3 shows the amplifier characteristics of the proposed PSA. Although the amplification band is L-band due to the limitation of the dispersion characteristics of the HNLFs, the amplification band can be freely selected [13]. If PSA pump and zero dispersion wavelength of the 3 highly nonlinear fibers (HNLFs) are aligned on a certain wavelength such as 1480nm, PSA gain profile would be adjacent to a longer wavelength range like from 1485nm to 1510nm. In this experimental result, the net gain of > 20 dB and the net NF of 0 dB (single-polarized wave) were achieved in the 25 nm band. By using this method, the equivalent transmission distance as that of C-band and L-band can be expected for amplification in new bands.

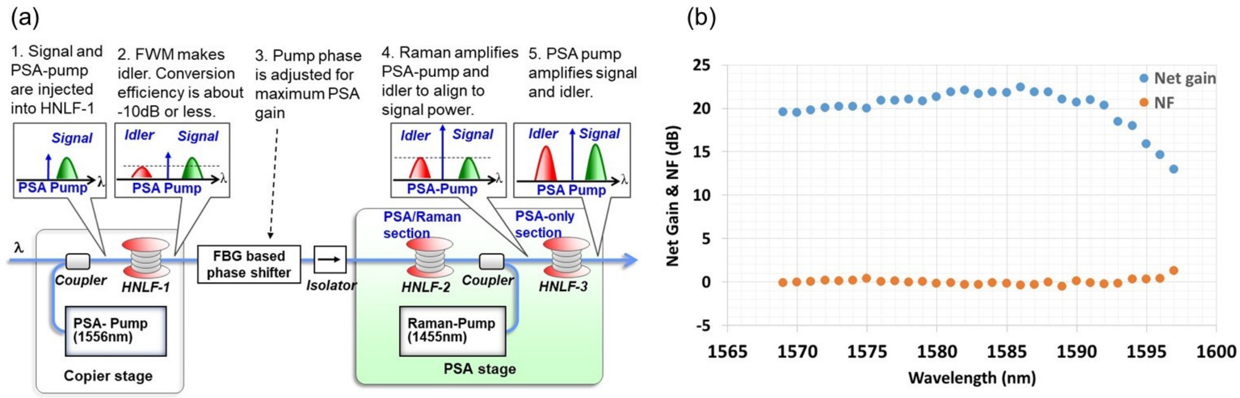

Fig. 2. (a) Configuration of the proposed Raman assisted Phase Sensitive Amplifier (PSA). (b) Net gain and Noise Figure (NF) of the proposed Raman assisted PSA. NF is calculated for single polarized signal.

5. Summary

In order to enable large-capacity optical transmission other than C-band and L-band, we introduced a new band amplification methods. The new band amplification combining parametric wavelength conversion and EDFA is suitable for short-haul networks such as between data centers, and the phase sensitive amplifier combining parametric wavelength conversion and Raman amplification is suitable for metro and long-haul. Further improvement of the characteristics of both methods is expected.

6. Acknowledgement

The Author thanks Shigehiro Takasaka and Ryuichi Sugizaki of Furukawa Electric Co., Ltd. for their suggestions and HNLF support. Also thanks to Cheng Guo and Professor Michael Vasilyev of University of Texas Arlington for their devoted efforts. The Author also appreciates Yinwen Cao of University of Southern California, Yasunori Obuki and Takeshi Hoshida of Advanced Technology Division of Fujitsu, for their support and encouragement.

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