Ultra-Wideband WDM Transmission Based on Multistage Raman Amplification

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***Abstract*—We propose a multistage Raman amplification structure for ultra-wideband wavelength division multiplexing (WDM) transmission. Simulation results show that the structure we propose can improve the general signal-noise-ratio and has a better performance.**

Keywords—Raman amplifier, ultra-wideband transmission, inter-channel stimulated Raman scattering.

I. INTRODUCTION

Ultra-wide band (UWB) wavelength division multiplexing (WDM) is an effective solution to meet the demand for high speed and large capacity for optical transmission networks [1], which can directly use the deployed optical infrastructure, thus delaying the deployment of expensive new optical fibers, and becoming a short-term solution to the problem of capacity contraction. In addition, this approach can co-exist with spatial division multiplexing.

One of the major problems of this scheme is the design of the optical amplifier. Thulium-doped fiber amplifiers (TDFAs) [2], semiconductor optical amplifiers (SOAs) [3] and Raman amplification [4] have been used in replace or in combination with EDFAs over the past few years to achieve milestones of data throughput in single-mode fiber (SMF) over different distances. Raman fiber amplifiers (RFAs) with combinations of Raman pumps are usually used to realize multi-band amplification. As long as the pump wavelengths and pump power are configured properly, RFA can be used to realize optical amplification at any wavelength. Furthermore, by adjusting the pump wavelengths and pump power, RFA can achieve a flat gain in ultra-wideband range.

Another problem of this scheme is the nonlinear effects, especially the inter-band stimulated Raman scattering (ISRS) [5] because the frequency shift between the short wavelength signal and the long wavelength signal is just near the peak of Raman gain due to the large frequency interval between them in this kind of UWB optical transmission system. Therefore, the transmission performance of the system is seriously limited by the energy transfer from the short wavelength signal to the long wavelength signal induced by ISRS, which leads to a significant reduction of the general signal-noise-ratio (GSNR) of the short wavelength signals, and a stronger nonlinear interference (NLI) of the long wavelength signals. Similarly, ISRS also occurs between pumps. The energy of the short-wavelength pumps used to amplify the short-wavelength signals will be transferred to the long-wavelength pumps used to amplify the long-wavelength signals, that is, there is a gain competition between the pumps and the signals, and the pump efficiency will be reduced due to the ISRS effect. The main method to eliminate ISRS is to optimize the signal launch power [6]. Predecessors have done a lot of work, so as to obtain the best system performance. The optimization methods include annealing algorithm [7], evolutionary algorithms (EAs) [8], particle swarm optimization (PSO) [9], global optimization [10] and machine learning [11]. Another solution is using a dual-stage discrete Raman amplifier [12] which requires special optical fiber with high nonlinearity and the whole Raman amplifier used is also specially customized. Inspired by this scheme, we choose to use a multi stage distributed Raman amplification structure. Instead of using high nonlinear fiber in Ref. [12], we directly use the transmission fiber as the Raman gain medium.

In this work, we propose a multistage Raman amplification structure, with Raman pumps distributed along the optical fiber link. By this way, the interaction between pumps can be suppressed, and we can improve the GSNR of short-wavelength signals and reduce the nonlinear interference of long-wavelength signals at the same time.

Theoretical analysis and simulation results show that the structure we proposed is effective.

II. PRINCIPLE

In order to maximize the information throughput of an optical communication system, it is vital to evaluate and maximize the performance of each individual channel that is transmitted. After coherent detection and electronic dispersion compensation, the channel dependent GSNR can be calculated as

$$GSNR(\lambda_i)=\frac{P_s(L,\lambda_i)}{P_{SpRS}(\lambda_i)+P_{ASE}(\lambda_i)+P_{NLI}(\lambda_i)} \quad (1)$$

where λ is the wavelength, subscript i refers to the i-th channel, $P_s(z,\lambda)$ is the signal power with wavelength λ at distance z, L is the total length of the transmission fiber, P_{SpRS} is the spontaneous Raman scattering noise, P_{ASE} refers to the amplified spontaneous emission noise generated by the EDFAs, P_{NLI} is the nonlinear interference calculated by the GN-model.

We use (2) to calculate the signal power and the spontaneous Raman scattering (SpRS) noise power. Propagation equations governing forward and backward power evolutions of pumps, signals and amplified spontaneous emission (ASE) in Raman amplifiers with Rayleigh scattering and temperature dependencies can be written as :

$$\begin{aligned}\frac{dP^{\pm}(z,\nu)}{dz}&=\mp\alpha(\nu)P^{\pm}(z,\nu)\pm\gamma(\nu)P^{\mp}(z,\nu)\\&\pm P^{\pm}(z,\nu)\sum_{\nu<\varsigma}\frac{g_R(\varsigma,\nu)}{K_{eff}A_{eff}}\left[P^{\pm}(z,\varsigma)+P^{\mp}(z,\varsigma)\right]\\&\pm h\nu\Delta\nu\sum_{\varsigma>\nu}\frac{g_R(\varsigma,\nu)}{A_{eff}}\left[P^{\pm}(z,\varsigma)+P^{\mp}(z,\varsigma)\right]\\&\cdot\left[1+\frac{1}{e^{h(\varsigma-\nu)/kT}-1}\right]\\&\mp P^{\pm}(z,\nu)\sum_{\nu>\varsigma}\frac{\nu}{\varsigma}\frac{g_R(\nu,\varsigma)}{K_{eff}A_{eff}}\left[P^{\pm}(z,\varsigma)+P^{\mp}(z,\varsigma)\right]\\&\mp 2h\varsigma\Delta\nu\sum_{\nu>\varsigma}\frac{g_R(\varsigma,\nu)}{A_{eff}}P^{\pm}(z,\nu)\left[1+\frac{1}{e^{h(\nu-\varsigma)/kT}-1}\right]\end{aligned} \quad (2)$$

where, ν and ς are the optical frequencies, the + and - symbols denote the propagation directions, α is the fiber loss, γ is the Rayleigh backscattering coefficient, $g_R(\varsigma,\nu)$ represents the Raman gain coefficient between frequency components ν and ς, A_{eff} is the effective area of the optical fiber, K_{eff} is the polarization factor between pump and Stokes signals, $K_{\text{eff}}=2$ when the polarization state of pump light and signal light is random, h is the Planck's constant, k is the Boltzmann constant and T is the Kelvin temperature. $\Delta\nu$ is the noise bandwidth.

According to (2), the spontaneous Raman scattering noise can be described as:

$$\begin{aligned}\frac{dP_{SpRS}(\lambda_i)}{dz}&=\left[-\alpha(\lambda_i)+\sum_j C_{R,ij}P_{p,j}\right]P_{SpRS}(\lambda_i)\\&+h\nu_i\Delta\nu\sum_j C_{R,ij}P_{p,j}F_{ij}\end{aligned} \quad (3)$$

where $C_{R,ij}$ is the Raman coupling coefficient between the i-th channel and the j-th pump, $P_{p,j}$ is the power of the j-th pump (sum of forward and backward), F_{ij} is the temperature dependent factor between the i-th channel and the j-th pump.

Nonlinear interference P_{NLI} is calculated by GN-model [13]:

$$P_{NLI}(\lambda_i)=\eta_n(\lambda_i)P_s^3(0,\lambda_i) \quad (4)$$

$$\eta_n(\lambda_i)=\frac{256}{27}\frac{\gamma^2}{R_b^2}\int_0^{\frac{B}{2}}\rho(\lambda_i)\frac{\sin^2(2n\pi^2f^2\beta_2L)}{\sin^2(2\pi^2f^2\beta_2L)}f\ln\left(\frac{B}{2f}\right)df \quad (5)$$

$$\rho(\lambda_i)=\left|\int_0^L P(z,\lambda_i)e^{j4\pi^2\beta_2f_i^2z}dz\right|^2 \quad (6)$$

where $\eta_n(\lambda_i)$ is the nonlinear interference coefficient at span n, γ is the nonlinear coefficient, R_b is the symbol rate, B is the total optical bandwidth, β_2 is the group velocity dispersion (GVD) parameter, $\rho(\lambda_i)$ is the four-wave mixing (FWM) efficiency factor which is determined by the signal power profile $P(z,\lambda_i)$, f_i is the frequency of the i-th channel. From (3) to (5) we know that P_{NLI} is positively correlated with signal power.

The research of Victor E. Perlin shows that the fundamental limits for the ratio of OSNR and the nonlinear weight in WDM systems with distributed Raman amplification are approached when the signal power variation along the fiber is minimized [14]. Based on this theory, we propose the multi-stage Raman amplification structure which can change the signal power profile to make it closer to a "lossless transmission". The comparison of a normal transmission link and the proposed structure is shown in Fig. 1. In the proposed structure, we introduce Raman pumps in stages. The total length of optical fiber and the total number of pumps have not been changed. The proposed structure can decrease the signal power variation, especially when the optical fiber link is long. The signal power will not be too high or too low in a certain section, because the pump power is devided into two stages and provides gain for the signal in each stage. By this way, we can improve the signal GSNR.

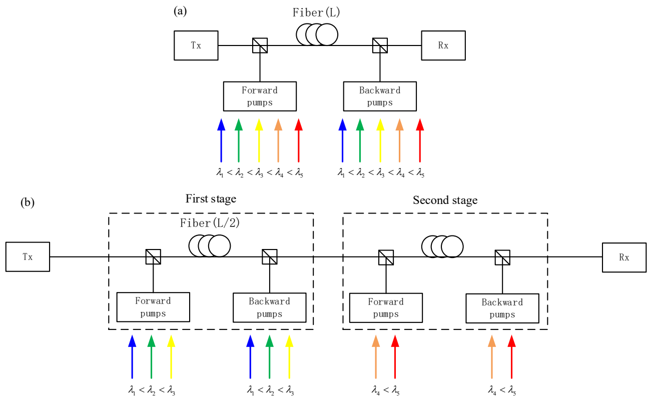

Fig. 1. (a) Normal transmission link; (b) Multistage Raman amplification structure

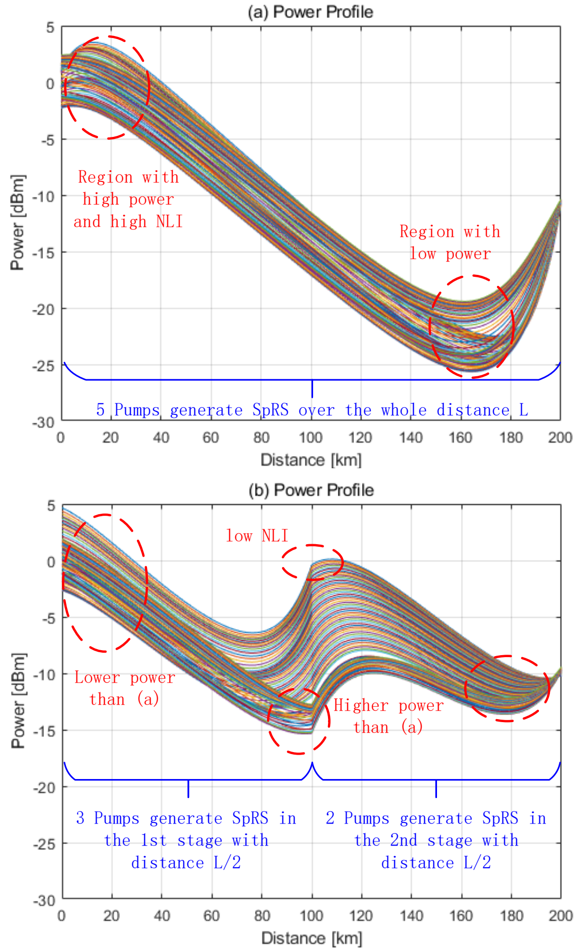

Fig. 2. Comparison of the signal power profile between (a) normal case with a single-span and (b) multistage Raman amplification structure

As shown in Fig. 2, we compared the signal power profile of normal case with a single-span and a two-stage Raman amplification structure. The pump power is set to be the same, and the only difference is the position where the pump is injected. In normal case, the signal power is at a high level near the transmitter thus introducing a high NLI, then it declines to a very low level at the receiving side. The 5 Raman pumps generate SpRS over the whole distance L. However, the NLI and SpRS will be reduced in the multistage Raman amplification structure. In the first stage, we use 3 short-wavelength pumps, which have a poor gain for long-wavelength signals, so the total power is reduced, which is helpful for suppressing the NLI. In the second stage, the long-wavelength signal gets significant gain because the Raman pumps in the second stage has a proper frequency interval with the long-wavelength signal. However, the long-wavelength signal power is already at a low level in this section, and the nonlinear interference is greatly reduced. Therefore, the use of multistage Raman amplification structure can suppress nonlinear noise.

According to (6), the SpRS noise consists of two parts: one part is generated by the pumps through spontaneous Raman scattering, and the other is that the noise undergoes the same loss and amplification as the signal along the link. Therefore, if the multistage Raman amplification provide the same total gain as that of a normal single-span transmission, then the value of the second part of P_{SpRSi} is equal. But the noise generated by spontaneous Raman scattering (the first part) will be reduced, because the pumps experience a shorter distance when transmitted along the fiber link.

On the other hand, when the gain of EDFA at the receiving end is fixed, P_{ASEi} is a fixed value, so the use of a multistage Raman amplification structure has no impact on this part of noise. To sum up, the use of multistage Raman amplification will reduce the nonlinear noise and spontaneous Raman scattering noise, but has no impact on the ASE noise generated by EDFA. The result is that the total noise power of the denominator in (2) is reduced, and the GSNR of the signal is improved.

III. RESULTS OF SIMULATION AND DISCUSSIONS

We have compared the performance difference between multistage Raman amplification and conventional single-stage Raman amplification in a bidirectional Raman amplification system with a total length of 200 km, as shown in Fig. 3. The transmitter is composed of 48 channels in C-band from 191.3 to 196.0 THz and 48 channels in L-band from 186.2 to 190.9 THz. There are three Raman pumps at both sides in the first stage, with the pump wavelength of 1425/1435/1450 nm, and two Raman pumps at both sides in the second stage, with the pump wavelength of 1465/1495 nm. There is a pre-amplifier at the receiving side with a fixed gain of 15 dB and NF of 5 dB for all channels. The fiber used in simulation is G.652 with a wavelength dependent attenuation of 0.2dB/km@1550nm.

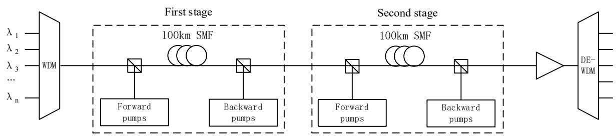

Fig. 3. System setup in the simulation

In order to achieve a fair comparison, we use gradient descent algorithm to optimize their pump power. The optimization target is the lowest value of GSNR of all channels, and the launch power pre-tilt makes the output signal power flat. By this way, we ensure that the system works in the best state in both cases.

We define ΔP_i to characterize the power flatness of signal transmission along the link:

$$\Delta P_i = \frac{\int_0^L \sqrt{\left(P_{si}(z)-\bar{P}_{si}\right)^2}\,dz}{\bar{P}_{si}} \tag{7}$$

where L is the total length of the fiber link, $\bar{P}_{si}$ is the average power of the i-th channel transmitted along the fiber link:

$$\bar{P}_{si} = \frac{\int_0^L P_{si}(z)\,dz}{L} \tag{8}$$

For normal transmission, the average value of ΔP_i is 234.13, and the maximum value is 241.18. For two-stage amplification transmission, the average value of ΔP_i is 147.73, and the maximum value is 187.77. As shown in Table I, the use of multistage Raman amplification can significantly reduce the power flatness of signal transmission along the link, both on the whole and in the worst case. According to the theory in Section 2, reducing the power flatness of signal transmission along the link can help improving the performance.

Fig. 4. shows the output spectrum and the GSNR of normal transmission and the multistage Raman amplification. In normal case, the total pump power after optimization is 1794.7mW, while under multistage Raman amplification transmission, the total pump power after optimization is 1712.1mW, which is also 82 mW lower than that under normal transmission. Under normal transmission, the output power flatness is 0.45 dB, the average output power is -10.59 dB; while by using a multistage Raman amplification structure, the output power flatness is 0.78 dB, the average output power is -9.81 dB. There is little difference of output signal power between the two cases. However, the GSNR has been significantly improved. Under normal transmission, the average GSNR is 24.38 dB, and the minimum GSNR is 23.28 dB. While under multistage Raman amplification, the average GSNR is 27.72 dB, and the minimum GSNR is 25.27 dB. It can be seen that the minimum GSNR is increased by 1.99 dB and the average GSNR is increased by 3.34 dB by adopting the multistage amplification structure. This proves that our proposed structure is helpful to improve system performance.

TABLE I

COMPARISON OF ΔP_i BETWEEN NORMAL TRANSMISSION AND TWO-STAGE AMPLIFICATION

	$(\Delta P_i)_{\text{ave}}$	$(\Delta P_i)_{\max}$
Normal Transmission	234.13	147.73
Two-stage Amplification	241.18	187.77

To help understand the reason for this performance difference, we plot and compare the power of the three kinds of noise in the denominator in (1) in Fig. 5 . It is not difficult to see from the figure that the SpRS noise is significantly reduced, and the NLI is reduced a lot especially for those channels with long wavelength, while the ASE introduced by the EDFA at the receiver side has little change because we set the parameters of EDFA to be fixed. The reduction of NLI is mainly due to the fact that the long-wavelength signal is first attenuated by the first section of optical fiber and then amplified by the second stage of Raman pump. Therefore, at the front end, or in the region with the highest power where the NLI should be max at this time, the NLI is suppressed. After half of the optical fiber transmission, the signal power is at a low level, and the excited nonlinear crosstalk is negligible. As for the SpRS noise, we divide it into two parts in (6). One part is generated by the Raman pumps through spontaneous Raman scattering along the fiber. The SpRS noise power of this part is only related to the pump power and transmission distance. The other part is that the first part of the SpRS noise is attenuated by fiber loss and amplified by the Raman pumps during transmission, and its power expression is consistent with the signal optical power. Therefore, reducing the pump power or pump transmission distance will reduce the first part of SpRS, thus reducing the final SpRS noise. In multistage Raman amplification, each stage of Raman pump has only experienced half of the transmission length, and the total pump power is also reduced, so the SpRS noise will decrease as well.

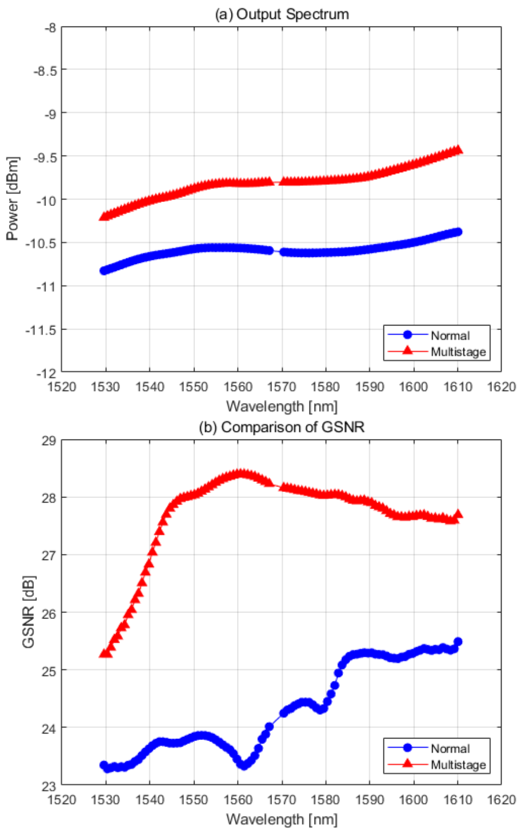

Fig. 4. Comparison of (a) the output signal power and (b) GSNR between single-span and multistage Raman amplification structure

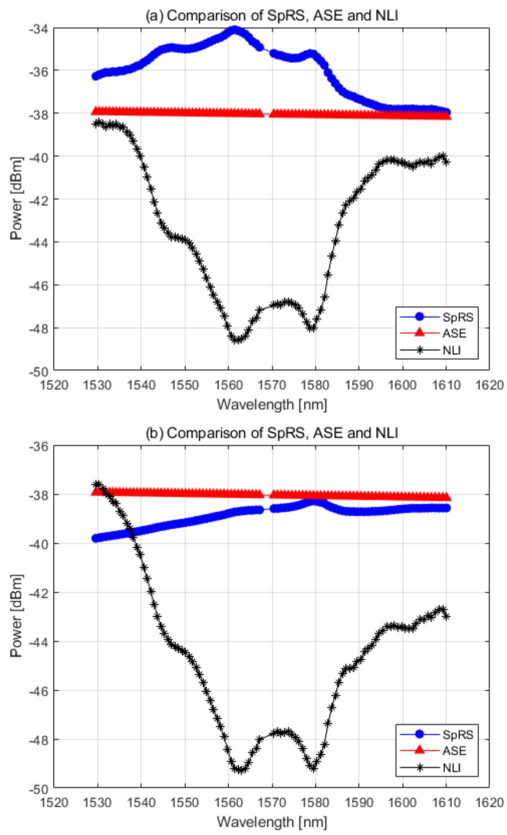

Fig. 5. Comparison of the noise power between (a) normal single-span and (b) multistage Raman amplification structure

IV. CONCLUSION

In this work, we propose a multistage Raman amplification structure, with Raman pumps distributed along the optical fiber link. Theoretical analysis shows that the SpRS noise and NLI of long-wavelength signals can be reduced by using our proposed structure. We demonstrate related simulation to prove that the structure proposed is effective. Simulation results show that the worst GSNR is improved from 23.28 dB to 25.26 dB in a 200 km G.652 fiber link with 96 channels (48+48) in the C+L band, while the total pump power configured along the fiber link can be reduced by 82.6 mW.

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