Fiber-bragg-grating-based dispersion-compensated and gain-flattened raman fiber amplifier

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Abstract: In this paper, we propose a novel signal/pump double-pass Raman fiber amplifier using fiber Brag gratings (FBGs). In order to compensate the dispersion slop mismatch among channels in lightwave system, FBGs embedded in different positions along dispersion compensated fiber are used to control the travel length of each WDM signal. Gain equalization can be achieved by optimizing the reflectivity of each FBG. Maximum output power variation among channels is less than ±0.5 dB after appropriate optimization. Finally, a wavelength division multiplexing (WDM) system using 40-Gb/s x 8 ch non return-to-zero (NRZ) signal transmission in a 100-km transmission fiber is simulated to confirm the system performance. Using proposed dispersion compensation method, it may lead to 2 dB improvement in Q value. Such kind of RFA may find vast applications in WDM system where dispersion management is a crucial issue.

OCIS codes: (060.2320) Raman fiber amplifier; (060.3735) Fiber Bragg Grating; (060.2330) Dispersion compensation.

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1. Introduction

Raman fiber amplifier (RFA) has become increasingly important in optical communication systems as a tool to counterbalance intrinsic fiber loss. Compared to erbium-doped fiber amplifier (EDFA), RFA has flexible signal gain region and relatively low noise figure (NF) level [1]. Recently, we reported a RFA with signal/pump double-pass scheme utilizing an optical circulator as a signal/pump reflector [2]. Pump efficiency improvement and NF suppression can be realized simultaneously. However, only single channel is studied. In a wavelength division multiplexing (WDM) system, dispersion slope mismatch between the DCF and the standard fiber will lead to huge residual dispersion which severely deteriorates maximum bandwidth and speed in a WDM system. Moreover, gain equalization among channels is required to confirm the uniform performance of bit error rate (BER) among WDM channels. For RFA, prior works either consider only the dispersion management or gain equalization issue. For example, prior work conquered WDM dispersion compensation in RFA system were appeared in [3] using dispersion compensation fiber. Or on the other hand, gain-equalization in RFA is studied in [4] using several pumps which wavelengths and pump power are optimized. Recently, *Wen et. al*. proposed a scheme by using fiber Bragg gratings (FBGs) embedded in the gain fiber to control the travel lengths of the WDM channels in RFA so that the accumulated-dispersion spectra of these signals in the amplifier can be tailored [5]. However, gain flattened in that work is too complicated and expensive because multiple pump lasers with wavelengths and power adjustment are required. For power equalization among WDM channels in EDFA, there is prior work dealing with the issue. For example, the authors used cascaded tunable FBGs to control the transmission loss for each channel via wavelength misalignment between the corresponding FBG and signal [6], assuming that the FBGs have V shape transmission spectra. Another equalization method using cascaded FBGs in reflection or transmission scheme is proposed by Rochette *et. al*. [7]. In this paper, we propose a new architecture of RFA based on signal and pump double-pass the gain medium and cascaded FBGs to increase the pumping efficiency. Beside gain equalization, but dispersion management could be realized simultaneously by only using single pump source.

2. Proposed scheme implementation

In a RFA-based WDM system, it is difficult to use only one segment of DCF for compensating WDM channels in the whole C and/or L-band. It is attributed to the mismatch of dispersion slope of the DCF and the standard fiber, usually the single mode fiber (SMF). In order to conquer this problem, several FBGs could be embedded in the DCF. In this work, each signal travel path in DCF is controlled by a FBG, which central wavelength is designed to match the signal wavelength. Each segment of DCF's length can be predicted based on the following equation:

$$L_{DCF} = -\frac{L_{SMF} D_{SMF}(\lambda)}{2D_{DCF}(\lambda)} \tag{1}$$

Where $D_{smf}(\lambda)$ and L_{smf} are the dispersion parameter and the length of SMF respectively, and $D_{dcf}(\lambda)$ is dispersion parameter of the DCF. Because the WDM signals pass through the DCF twice, there is a 1/2 factor in this expression path of the round-trip design. Figure 1 depicts the

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configuration of our proposed RFA. The WDM signals are fed into a 50 km SMF via a WDM multiplexer, and then travel through port 1 to port 2 of the optical circulator (OC). Together with the signals, Raman pump is launched into the dispersion compensation module (DCM) via a Raman coupler. The DCM is composed of several FBGs, several segments of DCF and a FBG-based pump reflector. Each FBG is matched with a certain signal channel separated. Inside the DCM, different signals travel through different lengths of DCF. For example, signal 1 only passes through the DCF 1 and then is reflected by the FBG 1, while signal 2 passes both the DCF 1 and DCF 2 and then is only reflected by the FBG 2 and so forth. The length of each segment of DCF is determined by using equation (1) to eliminate the residual dispersion of WDM signal channels. The Raman pump passes through the whole DCF and FBGs in the DCM firstly, and then the residual pump power comes back from the DCF again. Thus, the pump power double-passes the gain medium of the DCF to increase the pumping efficiency. In the double-pass scheme RFA, the forward and backward power evolution of pump, signals can be expressed in terms of the following equation [8].

$$\frac{dP^{\pm}(z,v_i)}{dz} = \mp\alpha(v_i)P^{\pm}(z,v_i) \pm P^{\pm}(z,v_i)\sum_{m=1}^{i-1}\frac{g_R(v_m - v_i)}{\Gamma A_{eff}}\left[P^{\pm}(z,v_i) + P^{\mp}(z,v_i)\right]$$
$$\mp P^{\pm}(z,v_i)\sum_{m=i+1}^{n}\frac{v_i}{v_m}\frac{g_R(v_i - v_m)}{\Gamma A_{eff}}\left[P^{\pm}(z,v_i) + P^{\mp}(z,v_i)\right] \qquad (2)$$

Where $P^+(z,v_i)$ and $P^-(z,v_i)$ are optical power of the forward and the backward propagating waves within infinitesimal bandwidth around v_i respectively. $\alpha(v_i)$ is the attenuation coefficient of the corresponding wavelength v_i. A_{eff} is effective area of optical fiber; $g_R(v_i-v_m)$ is Raman gain parameter at frequency v_i due to pump at frequency v_m; the factor Γ accounts for polarization randomization effect, which value lies between 1 and 2. Besides dispersion compensation, we may also carry out the gain equalization by adjusting the reflectivity of each FBG. Here, the objective function is

$$f_i(R_i) = abs\left(\frac{P_i - avg[P(R)]}{avg[P(R)]}\right) \qquad i \in [1, N] \qquad (3)$$

Where $P_i(R)$ is the signal power of the ith WDM at FBG with reflectivity R_i, and our aim is to minimize the objective function to zero. Considering possible large channel number in a real WDM system, we use Broyden method [9-10] as it is powerful in solving nonlinear systems equations. It is globally convergent and it provides an easier approximation to the Jacobian matrix for zero finding. The proposed DCF module is a nonlinear system as proper dispersion compensation and FBG reflectivity have to be determined.

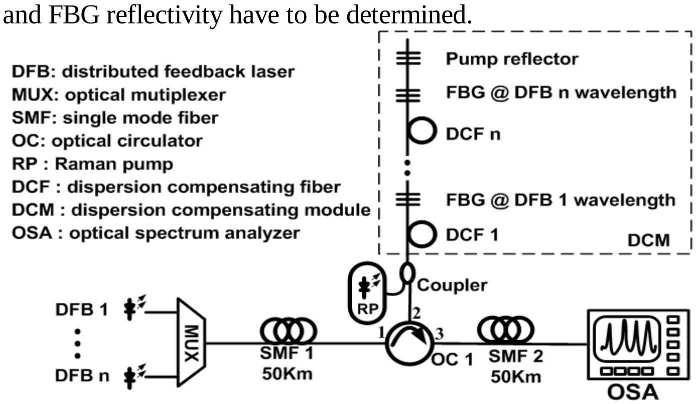

Fig. 1. Configuration of the proposed RFA.

3. Simulation results and discussion

The feasibility of configuration shown in Fig. 1 is carried out by simulation tool. Without loss of generality, there are eight-WDM-channel inside the C-band, staring from 1530.8 nm to 1553.2 nm with channel spacing based on ITU grid of 400 GHz (3.2 nm), with 0 dBm as the

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launched power level for each channel. Here, we would rather demonstrate the broadband RFA ability than crosstalk issue in a dense WDM system. The central pump wavelength is at 1451 nm with pump power of 333 mW. In practice, this pump power level can be realized by combining two orthogonal, polarized pump lasers to obtain total higher power using a polarization beam combiner (PBC). As referred to [11], the signal absorption coefficients may choosed be to 0.2 dB/km and 0.3 dB/km for SMF and DCF, respectively. And the pump absorption in DCF is 0.55 dB/km. The Raman gain coefficient and the effective area of DCF are assumed to be identical with those in [12]. Firstly, we use the dispersion map to determine the length of each DCF segment. In our simulation, the dispersion of SMF is 17 ps/nm/km at 1550 nm with dispersion slope of 0.058 ps/km/nm^2; and the dispersion of DCF is -95 ps/nm/km at 1550 nm with dispersion slope of -0.62 ps/km/nm^2. In a conventional configuration, the dispersion compensation is carried out by using only one segment of DCF, transmission bandwidth or transmission speed is surely restricted. As shown in Fig. 2, if we want to minimize the system residual dispersion in the conventional configuration, the length of DCF is equal to 9.1 km. In this condition, the maximum absolution of residual dispersion, which appears both in the longest and the shortest wavelengths are +62 ps/nm and -62 ps/nm, respectively. So, the maximum transmission speed Rb is limited to 23 Gbit/s, as could be predicted by the following equation [13]:

$$R_b = \sqrt{\frac{\mathrm{C}}{4|D_{res}|\lambda^2}} \tag{4}$$

Where C is the speed of light in vacuum, Dres is the residual dispersion and λ is the central wavelength.

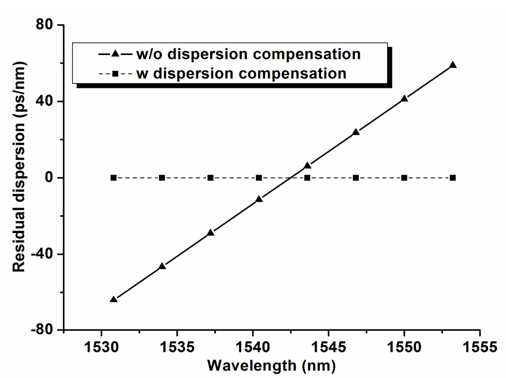

Fig. 2. Residual dispersion of the RFA versus signal wavelength.

By using DCM composed of FBGs in among several DCF segments, the residual dispersion shown in Fig. 2 can be theoretically eliminated. Beside the common DCF of 8860 m in length, the calculated extra-length of DCF required are 0-, 87-, 91-, 95-, 99-, 103-, 108- and 113 m, for WDM-channel of 1553.2-, 1550.0-, 1546.8-, 1543.6-, 1540.4-, 1537.2-, 1534.0-, and 1530.8 nm, respectively. For the study of gain equalization, the reflectivity of each FBG is assumed to be 100% in the beginning. Note that the FBGs inside the DCM are uniform gratings rather than chirped FBGs. It is DCF that play the sole role to deal with the chromatic dispersion issue. As shown in Fig. 3(a), the solid curve depicts the output power when the FBGs are written at the correct positions for optimum dispersion compensation. The maximum power variation among channels is nearly 6 dB and the lowest output power is at the shortest wavelength. In order to equalize the output power, the FBG reflectivity corresponding to the lowest signal is set to 100% and other reflection ratios of FBGs are optimized using the Broyden method. As shown in Fig. 3, when the reflectivity of FBGs are designed 19.67%, 19.1%, 21.34%, 26.45%, 33.37%, 44.93%, 64.58% and 100%, respectively,

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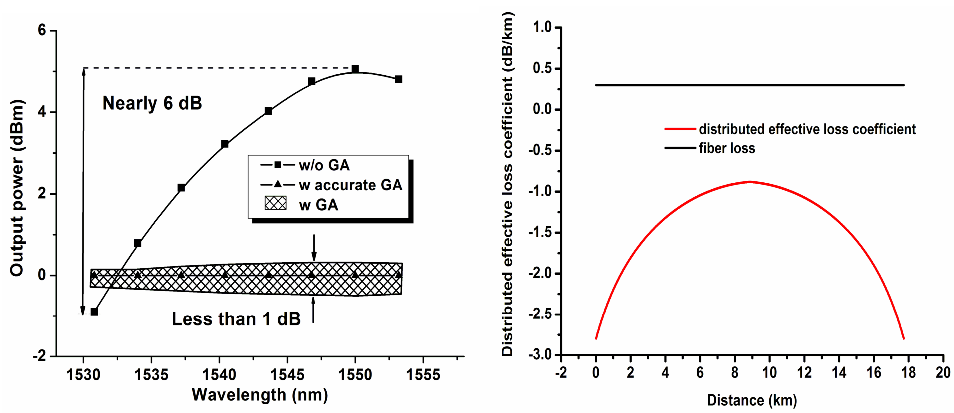
the eight WDM channels are power equalized simultaneously. In our lab, the home-made FBG's reflection ratio can be precisely controlled within ±5% accuracy easily. The output power of all channels could be fell into the shadow region shown in Fig. 3(a), which indicates that the maximum output variation is less than ±0.5 dB as expected. Note that the flattened amplification bandwidth is as large as 23 nm even that only a single pump laser is used in this study. In this case, the splicing loss of FBG-DCF junction and sideband loss of FBG are assumed negligible for simplify. On the other hand, if we assuming that the absorption coefficient of DCF increases to 0.5 dB/Km as some commercial products, the required pump power will increase a little bit to 383 mW for obtaining the same net gain. The reflectivity of FBGs then are modified as 21.3%, 19.8%, 21.4%, 26.0%, 32.3%, 43.3%, 62.8% and 100% for the corresponding channels. In our recent works, we successfully proved that the simulated result [8] for RFA agree well with that of the experimental work [2]. So, the simulated performance is realistically achievable because similar technique is applied here.

To confirm the system feasibility, a comprehensive numerical simulation of the signal transmission characteristics in lightwave system employing this RFA is evaluated. Two configurations, with and without residual dispersion compensation are employed in our simulation for comparison. A pseudo-random-binary-sequence (PRBS) 10^{23}-1 non-return-to zero (NRZ) formats is applied to intensity modulation of WDM channels in 40 Gb/s speed for each channel. The total signal envelope propagates through the fiber span including 100 km SMF is modeled by the modified nonlinear Schrödinger equation (NLSE) [14].

$$i\frac{\partial A_j}{\partial z}+\frac{i}{v_{gj}}\frac{\partial A_j}{\partial t}-\frac{1}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial t^2}+\frac{i}{6}\beta_{3j}\frac{\partial^3 A_j}{\partial t^3}+\gamma(\left|A_j\right|^2+2\sum_{m\neq j}^{M}\left|A_m^2\right|)A_j=\frac{i\alpha}{2}A_i \tag{5}$$

where v_{gj} is group velocity of jth channel, β_{2j} is group velocity dispersion (GVD) parameter, β_{3j} is third-order dispersion (TOD) parameter, γ is nonlinear coefficient, and α accounts the loss. We incorporate the signal/pump double-pass Raman amplification effect by adding the distributed RFA gain coefficient into the NLSE [3]. The calculated equivalent fiber loss for the first channel is shown in Fig. 3(b) and the DCF's loss coefficient is also plotted as well. The RFA in simulation can provide 20-dB of net gain.



(a) (b)

Fig. 3. (a). Output power of the RFA versus signal wavelength. Fig. 3(b). Distributed effective loss coefficient of signal 1 along DCF.

Then we compare two different schemes of residual dispersion compensated and without residual dispersion compensation. For example, one may write the FBGs at the same position for the latter case. In both schemes, the total loss attributed by 100 Km SMF are compensated completely by the RFA. The BER with respect to the input signal wavelength is shown in Fig. 4(a). The error-free condition (BER $\leq 10^{-11}$) could be obtained as non-return-to-aero (NRZ)

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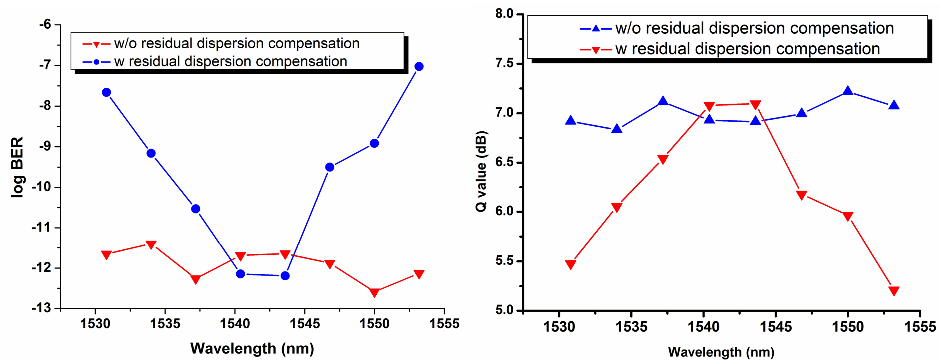
data format is used. On the other hand, without residual dispersion compensation will lead to worse system performance both for the shortest and the longest wavelengths. In our simulation, only three kinds of impairments such as amplifier accompany noise, residual dispersion and nonlinearity are considered to be the overall impacts to close the eye diagram. In such condition, the noise will be a Gaussian distribution [15]. So, equation 6 could be used to convert Q value to BER directly.

$$BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \tag{6}$$

where erfc is the error function. As shown is Fig. 4(b), The Q values are all larger than 6.6 dB for all WDM channels by using the proposed method to compensate the residual dispersion. Otherwise, it will lead to as large as 2 dB degradation in Q value corresponding to BER degradation from 10^{-12} to 10^{-7} for both the longest and the shortest wavelengths. These results confirm the feasibility of RFA we proposed.



(a) (b)

Fig. 4. (a) BER as a function of input signal wavelength, and (b) Q value as a function of input signal wavelength.

4. Conclusion

In summary, we have proposed a novel RFA with both dispersion management and gain equalization characteristics based on FBGs. In order to compensate the dispersion slope mismatch between the transmission fiber and DCF, FBGs embedded in the different positions are used to control the travel length of each WDM signal. Gain equalization can be achieved by optimizing the reflectivity of each FBG. Maximum output variation is less than ±0.5 dB when the FBGs' reflectivity are precisely controlled. A PRBS 10^{23}-1 NRZ formats is applied to intensity modulation the WDM channels in 40 Gb/s x 100-km SMF system to confirm the ability of residual dispersion compensation. We find that the Q value is improved by nearly 2 dB corresponding to BER is improved from about 10^{-7} to 10^{-12} for both the longest and the shortest wavelengths. Such kind of RFA may find vast application in WDM system where dispersion management and power equalization is a crucial issue.

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