Time-wavelength-mode equalization by PSO for random fiber laser based FMF Raman amplifier

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Abstract: We report an FMF Raman amplifier based on random fiber laser with optimized time-wavelength-mode equalization by PSO method, achieving 1.3-dB spectral gain flatness, 2.3-dB temporal SPV, and 0.03-dB MDG with 15-dB on-off gain. © 2020 The Author(s)

1. Introduction

Mode division multiplexing (MDM) systems utilize different modes in few-mode fibers (FMF) as independent channels to significantly increase communication capacity, which has been attracting broad interests in recent years [1]. Distributed Raman amplifiers (DRA) and Erbium doped fiber amplifiers (EDFA) are the two main amplification schemes in optical communication [2][3]. Compared to EDFA, DRA has lower noise and reduced nonlinear distortion because of its distributed architecture. This is of great importance, as long haul transmission systems and advanced modulation formats require higher signal-to-noise ratio (SNR). It is of greater importance for MDM system since higher nonlinear distortion will be expected due to increased power density in the FMF. Moreover, flexible bandwidth and gain spectrum profile design can be easily achieved by adjusting pump wavelength and power of the DRA. Equalized amplification in time and wavelength domain leads to balanced performance of noise and nonlinearity, like a quasi-lossless transmission link [4]. In MDM systems, one can also reduce mode dependent gain (MDG) by adjusting mode power of pumps. The increased mode dimension of MDM makes the optimization of FMF amplification rather difficult and thus three-dimensional equalization is highly desired.

DRA introduces two kinds of noise, the amplified spontaneous emission (ASE) noise and relative intensity noise (RIN) which is generated by RIN of pump lasers [5]. In MDM systems, another challenge is SNR penalty caused by crosstalk between modes. MDG is another significant indicator to evaluate the performance of few mode DRA, which requires the difference in gains of all modes as small as possible. Several methods have been proposed to enhance the transmission performance of single mode DRA, but they have not been utilized on FMF. A powerful scheme is the random fiber laser structure with a single fiber Bragg grating at output port, with which first order Raman laser is stimulated by second order Raman pump and then amplifies the signals [6]. This scheme effectively reduces RIN from pumps and offers incredible noise performance. Moreover, this scheme shows lower signal power variation (SPV), also providing better SNR property and another superiority, reduced nonlinear distortion.

In order to achieve low noise (particularly low RIN) and low nonlinearity of MDM transmission, we demonstrate a random fiber laser based FMF DRA with optimized time-wavelength-mode equalization. The FMF DRA supports 2-LP modes, C-band with 70-km FMF. We apply particle swarm optimization (PSO) method for the time-wavelength-mode equalization optimization. 1.3-dB spectral gain flatness, 2.3-dB temporal SPV, and 0.03-dB MDG with 15-dB on-off gain is achieved based on the proposed DRA structure and optimization method.

2. Principle and algorithm

Fig. 1 shows the proposed two configurations of DRA based on bidirectional pumped random fiber laser, providing continuous gain covering C-band. In both configurations, four first order Raman pumps at 1420 nm, 1435 nm, 1445 nm and 1475 nm and second order Raman pump at 1375 nm are employed as Raman pumps, launched into mode (de)multiplexers at both ends of the FMF. Mode (de)multiplexer couples all modes of signals and pumps into FMF. These mode (de)multiplexers are set as ideal (de)multiplexers because we only simulate the stimulated Raman scattering and attenuation in FMF. In Fig. 1(a), few mode FBGs at 1420 nm, 1435 nm, 1445 nm, 1475 nm are placed at middle of 70-km FMF and all pumps are bidirectional pumps. Fig. 1(b) displays the conventional random fiber laser configuration with the FBGs placed near output end of FMF. Four first order pumps and second order pump are used as forward pumps and backward pump, respectively. Two types of two-mode FBG scheme, 4-FBG and 8-FBG, are used according to their reflection characteristics [7]. Each FBG in 4-FBG scheme reflects pump of corresponding wavelength into another mode and each FBG in 8-FBG scheme reflects pump of corresponding wavelength and mode into the same mode. The FMF attenuations of C-band signal, first order Raman pump and second order Raman pump are 0.2 dB, 0.277 dB and 0.349 dB, respectively. In total, 36 signal wavelengths from 1530 to 1565 nm are utilized and the input power is -10 dBm per wavelength per mode channel.

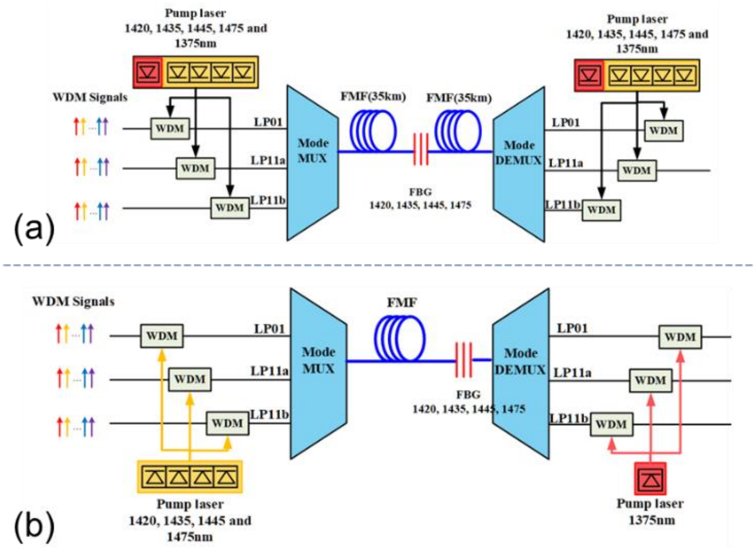

Fig. 1. Configurations of DRA with few mode FBGs (a) placed at the middle of FMF and (b) placed near the output end of FMF.

Propagation equations governing forward and backward power evolutions of signals and pumps and the intensity overlap integrals of the FMF are presented in Ref. [8]. Then, we can substitute the wavelength and the input power of signals and pumps into propagation equations and solve it using Runge-Kutta method and release method. Power evolutions of all signals and pumps are calculated.

To implement time-wavelength-mode equalization, optimization algorithm is employed to minimize mode dependent gain (MDG), SPV and spectral gain flatness. The pump power of each wavelength and mode is the parameter to be optimized. Therefore, total 11 parameters are set as variables, containing pump power per wavelength per direction and power ration. A set of targets, consisting of SPV, gain flatness and MDG, will be calculated by substituting a set of 11 variables, which can be taken as a target function. We set the target function as the sum of SPV, gain flatness and MDG. The optimization algorithm we select is particle swarm optimization (PSO) [9]. A population of particles are initialized randomly with positions and velocities and they will fly in the problem space. Positions and velocities of each particle will be updated according to equations (1) and (2).

$$V_{id} = V_{id} + C_1 random(0,1)(P_{id} - X_{id}) + C_2 random(0,1)\left(P_{gd} - X_{id}\right) \tag{1}$$

$$X_{id} = X_{id} + V_{id} \tag{2}$$

V_{id} and V_{id} is particle's velocity and position, respectively. P_{id} is individual best position and P_{gd} is global best position. Individual best position is defined as the best position associated with best value of the target function each particle has found. Global best position is defined as the best position of all individual best positions. C_1 and C_2 is acceleration constants, equal to 2 for most applications. Maximum velocity on each dimension is necessary to be limited, often set at 10-20% of the range of variables on each dimension. Compared with genetic algorithm, PSO is attractive because there are few parameters to adjust. Moreover, PSO has better convergence speed.

3. Results and discussions

The optimized pump powers of the configuration shown in Fig. 1(a). In fact, if the percentage of LP_{01} mode pump and LP_{11} mode pump is 10.2% and 89.8% respectively, MDG will be reduced in an extreme low level. But in the scheme with 4-FBG, two mode FBGs convert the mode of reflected pumps and it is difficult to maintain the percentage of each mode pump power. Therefore, in this circumstance, launched pump power of each mode needs to be optimized by algorithm. It can be observed that two configurations with different FBG schemes have similar performance. The optimized on-off gain profiles and signal power evolutions are shown in Fig. 2. Because the signal power evolutions of two modes are almost identical, only LP_{11} mode is presented.

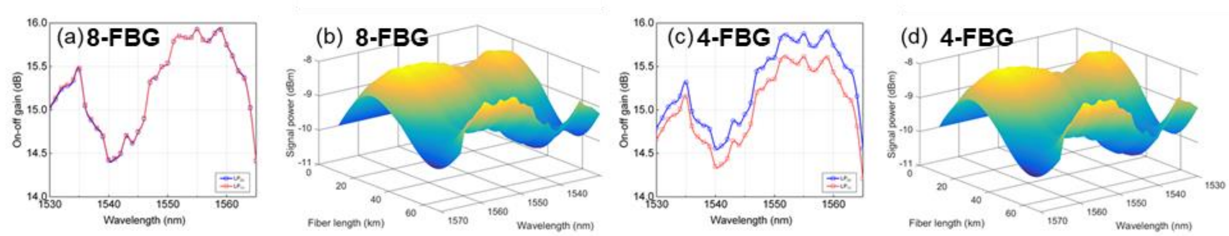

Fig. 2. The result of the configuration with FBGs placed at the middle of FMF. (a) gain profile and (b) LP_{11} mode signal power using 8-FBG scheme. (c) gain profile and (d) LP_{11} mode signal power using 4-FBG scheme.

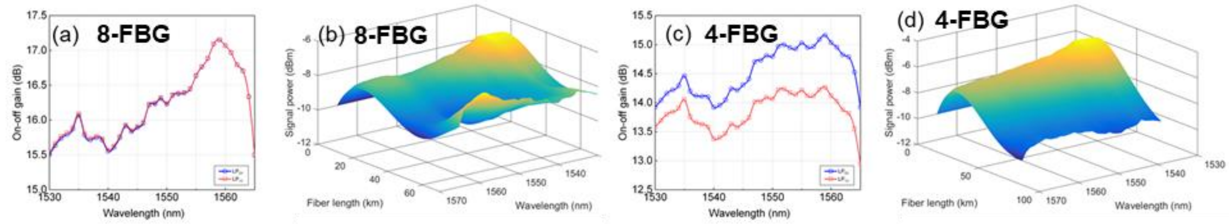

Fig. 3. The result of the configuration with FBGs placed at the output end of FMF. (a) gain profile and (b) LP_{11} mode signal power using 8-FBG scheme. (c) gain profile and (d) LP_{11} mode signal power using 4-FBG scheme.

The average on-off gain for the DRA is about 15 dB and the overall gain variation is about 1.5 dB. The maximum MDG of 4-FBG configuration and 8-FBG configuration is about 0.35 dB and 0.03 dB, respectively. The SPV, defined as the difference between maximum and minimum of the surface, is about 2.3 dB. As a comparison, the optimization results and performance of conventional random fiber laser configuration are shown in Fig. 3. This configuration employs fewer number of pumps and it is easier to implement. The performance of on-off gain, overall gain variation and MDG is similar to the configuration shown in Fig. 1(a). But SPV is increased to 3.0 dB using 8-FBG and 5.0 dB using 4-FBG. We adjust the pump powers and find that SPV using 4-FBG can be reduced, which will result in higher MDG of more than 2 dB.

4. Conclusion

In this paper, we reported a time-wavelength-mode equalization method for low noise and low nonlinearity FMF DRA based on two configurations of bidirectional random fiber laser. We achieved gain variation of 1.3 dB, MDG of 0.03 dB and SPV of 2.3 dB at 15-dB on-off gain by PSO optimization algorithm.

Acknowledgement

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