

DCF-based fiber Raman amplifiers with fiber grating reflectors for tailoring accumulated-dispersion spectra

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Abstract

The fiber Raman amplifier (FRA) using dispersion-compensation fiber (DCF) as the Raman fiber is studied. Fiber grating reflectors (FGRs) embedded in the amplifier are used to control the travel lengths of the WDM signal channels in the amplifier so that the accumulated-dispersion spectra of the signals in the amplifier can be tailored. The amplifier compensating for the accumulated dispersions of 86 ITU 100 GHz-spaced WDM signal channels in 100 km TrueWave-RS fiber and providing 20 dB gain for each channel is taken as an example, in which the positions of FGRs in the DCF ranges from 2.18 km to 2.68 km. It is shown that its pump power can be utilized more efficiently than the conventional FRA without FGRs. The FGRs can be written on the DCF or inserted into the DCF by splicing. For the latter case, the pump power and noise figure are respectively increased by about 86.6 mW and 0.2 dB per 0.01 dB loss increment of a splice point.

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1. Introduction

Signal propagation in an optical fiber experiences the fiber loss and dispersion that limit the transmission distance and bit rate. In a broadband wavelength-division-multiplexing (WDM) system, the fiber loss and dispersion depend on the signal wavelength. The fiber loss can be compensated by the optical amplifiers such as the erbium-doped fiber amplifier (EDFA) and fiber Raman amplifier (FRA) [1–3]. The FRA has the advantages of the broad gain bandwidth, in which its gain band depends on the pump wavelength. The shape of the gain spectrum of an FRA can be tailored by the use of the multiple pumps of different wavelengths [4]. Fiber dispersion can be compensated by the use of the dispersion compensation fiber

(DCF). DCF is usually also used as the Raman fiber of the lumped FRA. The Raman gain of the DCF is high because of its small effective fiber area and high Ge-dopant concentration. The dispersion parameter of the DCF is negative and its absolute value is large so that the DCF of short length is able to compensate for the positive accumulated dispersion of the transmission fiber such as the standard fiber (STF) and the non-zero dispersion-shifted fiber (NZDSF). There are the DCFs for commercial existing transmission fibers in 15xx wavelength region. The relative dispersion slope to dispersion (RDS) is defined for the dispersion compensation in WDM systems. For complete dispersion compensation over all signal wavelengths, it requires that the RDSs of the transmission fiber and DCF are the same. Otherwise, there is the residual dispersion that limits the usable wavelength range for WDM systems [5]. However, in practice, the RDSs of the transmission fiber and DCF are not exactly matched and

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that is due to the design of the DCF and manufacturing variation. For the WDM system of ultra-high bit rate per channel, e.g. 160 Gb/s and above, the usable wavelength range is further limited because, it is required to consider the residual dispersion in a range equivalent to the spectral width of the signal [5]. For the signal channels that their dispersion cannot be compensated, they have to be de-multiplexed. Thus their dispersions can be respectively compensated by the DCFs of proper lengths. To overcome this deficiency, it was proposed to use fiber grating reflectors (FGRs) at different positions in the DCF for controlling the travel lengths and accumulated dispersions of the WDM signal channels in the DCF [6]. Thus, the dispersions of the WDM signal channels can be compensated in the DCF without de-multiplexing.

Since the DCF can also be used as the Raman fiber, the DCF-based FRA can be designed to compensate for both the fiber loss and dispersion simultaneously [5,7]. In this paper, we consider the DCF-based FRA using the FGRs to tailor its accumulated-dispersion spectra, which is called the FRG dispersion-tailored FRA (FGR-DT-FRA). The conventional FRA without FGRs is denoted as CFRA. In [6], the non-chirped fiber gratings are used as the reflectors. However, there is the dispersion slope within the reflection band for a non-chirped fiber grating. As the fiber gratings are used as the reflectors in the FGR-DT-FRA, the chirped fiber gratings of low dispersion [8] can be used as the FGRs, so that the accumulated dispersions of the WDM signal channels depend only on their travel lengths in the DCF. The FGRs can be directly written on the DCF of the FRA or can be inserted into the DCF by splicing. For the latter case, the FGR can be manufactured by writing the grating on the DCF of short length. Thus the splice loss can be minimized because the mode field diameters of the inserted FGR and the DCF of the FRA are the same. The performances of the FGR-DT-FRAs with and without the splice loss will be investigated. As the signals are reflected within the FGR-DT-FRAs, they experience double pass gain. It will be also shown that, even with typical splice loss, the required pump power of the FGR-DT-FRAs is less than that of the CFRA.

2. Amplifier model and numerical parameters

The Raman amplification in a FRA can be described with a set of coupled differential equations that represent the steady-state power evolutions of pumps, signals, Rayleigh scattering noise, and amplified spontaneous emission noise (ASEN) [9]. Double Rayleigh scattering (DRS) is included in numerical simulations [10], in which the noise power comprises not only the single-pass ASEN power but also the DRS power of the signal and ASEN. The coupled equations are numerically solved by iteration [11]. When the waves reach a FGR, their powers are attenuated by two times of the splice loss of the FGR because there are two splice points for an inserted FGR. The loss of a splice point is denoted by S . For the signal and ASEN, if their

frequencies coincide with the reflection frequency of the FGR, they are split into the forward and backward waves according to the reflectivity of the FGR and their propagating directions. The reflectivity of a FGR is taken as R . The splice losses and reflectivities of all FGRs are assumed to be the same for simplicity.

Eighty six signal channels following ITU grid are considered, in which their wavelengths are spaced 100 GHz and from 1530.61 nm to 1600 nm. For each channel, we assume that the signal power launched into the FRA is -23 dBm and the required signal gain is 20 dB. The position separation between neighboring FGRs increases with the difference of the RDSs of the transmission fiber and DCF. For the case that their RDSs are about the same, the separation is short and all the FGRs are located nearby the end of the DCF. In this paper, we consider the more interesting case that the RDSs differ much and the separation is long. This case shows that the dispersion compensation with the FGRs is flexible and less limited. We take TrueWave-RS fiber as the transmission fiber in which the dispersion parameter and dispersion slope of the considered transmission fiber are 4.5 ps/(km nm) and 0.045 ps/(km nm²), respectively [5]. HSDK fiber is taken as the DCF, in which the dispersion parameter and dispersion slope of the considered DCF are -95 ps/(km nm) and -0.62 ps/(km nm²), respectively [5]. If this DCF is used to compensate for the dispersion of TrueWave-RS fiber without FGRs, we may estimate the usable wavelength range by assuming that the transmission length is only limited by residual dispersion. For example, the residual dispersion within ± 0.05 ps/(km nm) corresponds to a theoretical transmission length of 1200 km for an NRZ signal at 40 Gb/s [5]. Such residual dispersion limits the usable wavelength range to be only 6.4 nm. With 1460 nm polarization-scrambled pump, the Raman gain coefficient of the DCF has the peak value of 3.16 1/(W km) at the frequency shift of 13.05 THz. The fiber loss, effective area, and Rayleigh scattering coefficient at 1550 nm are 0.6 dB/km, 15 μm^2 , and -32.3 dB/km, respectively. The temperature of thermal noise is 300 K. The FGR position in the DCF for reflecting the signal at the wavelength λ is

$$z_g(\lambda) = -\frac{D_t(\lambda)L_t}{2D_{\text{dcf}}(\lambda)}, \quad (1)$$

where $D_t(\lambda)$ and L_t are the dispersion parameter and length of the transmission fiber, respectively; $D_{\text{dcf}}(\lambda)$ is the dispersion parameter of the DCF; the 1/2 factor is included because the travel length of the signal within the DCF is $2z_g$. In this paper, $L_t = 100$ km is taken as an example. With the parameters given above, Fig. 1 shows the FGR position versus signal wavelength. One can see that the FGR position increases with signal wavelength. The length between neighboring FGRs ranges from 4 m to 8.4 m. However, for field applications, the length between the neighboring FGRs can be tailored according to the measured dispersion characteristics of the DCF and the deployed transmission fiber. We also consider the CFRAs

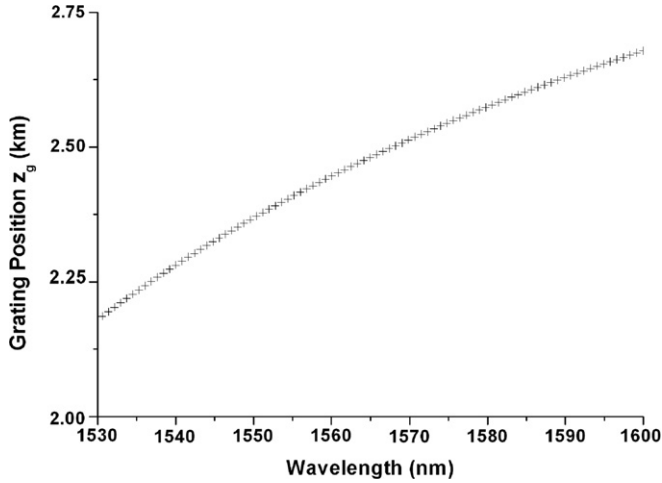


Fig. 1. FGR positions in DCF.

for comparing their pump powers and noise performances with that of the FGR-DT-FRA. The lengths of all the considered FRAs are 2.68 km. The considered FGR-DT-FRA forward pumped by eight pumps are used so that the gain ripple can be reduced to less than 0.1 dB by optimizing the pump wavelengths and powers. Two CFRAs using forward pumping and backward pumping are considered for comparing with FGR-DT-FRA, in which their numbers of pump wavelengths are also eight. The objective function for minimizing gain ripple is

$$h(\mathbf{A}) = \sum_{k=1}^{N_s} (G_k(\mathbf{A}) - G_{kT})^2, \quad (2)$$

where $N_s = 86$ is the number signal channels, $G_k(\mathbf{A})$ is the gain of the k th signal channel for the vector $\mathbf{A}$ that comprises the numerical values of the pump wavelengths and powers; G_{kT} is the target gain of the k th signal channel. The target gain of each signal channel is taken to be 20 dB. Modified Levenberg–Marquardt method is used to minimize the objective function [12]. In every searching step, the signal gains are obtained by solving the coupled differential equations of the FRA. For the broadband FRAs using multiple pumps, the long-wavelength pumps are significantly amplified by the short-wavelength pumps. Therefore the injected powers of the long-wavelength pumps are designed to be less than that of the short-wavelength pumps. From Fig. 1, because the long-wavelength signals are reflected after the short-wavelength signals, the FGR-DT-FRA is designed to be forward pumped so that the long-wavelength pumps penetrate deeper into the DCF, owing to the pumping of the short-wavelength pumps. On the contrary, if the long-wavelength signals were reflected before the short-wavelength signals, then the FGR-DT-FRA would be designed to be backward pumped.

3. Numerical results and discussion

At first, we consider the FGR-DT-FRA without splice loss, i.e. the FGRs are written on the DCF of the FRA

rather than inserted into the DCF by splicing. Fig. 2a shows the pump power spectra of the FGR-DT-FRAs and the CFRAs, in which the cases with $R = 90\%$ and 100% for the FGR-DT-FRAs are shown. The pump wavelengths and powers of the FGR-DT-FRA with $R = 100\%$ are optimized first. For the FGR-DT-FRA with $R = 90\%$, its pump wavelengths are the same as the optimized pump wavelengths of the FGR-DT-FRA with $R = 100\%$, so is the FGR-DT-FRA with splice loss that will be shown later. Thus only its pump powers are optimized for reducing the gain ripple to be less than 0.1 dB. From Fig. 2a, the required powers of the short-wavelength pumps of the FGR-DT-FRAs are smaller than that of the CFRAs. The total pump powers are 1006 mW and 987 mW for the FGR-DT-FRAs with $R = 90\%$ and 100% , respectively. The total pump powers are 1697 mW and 1722 mW for the CFRAs using forward and backward pumping, respectively. The pumping efficiency of the FGR-DT-FRA is

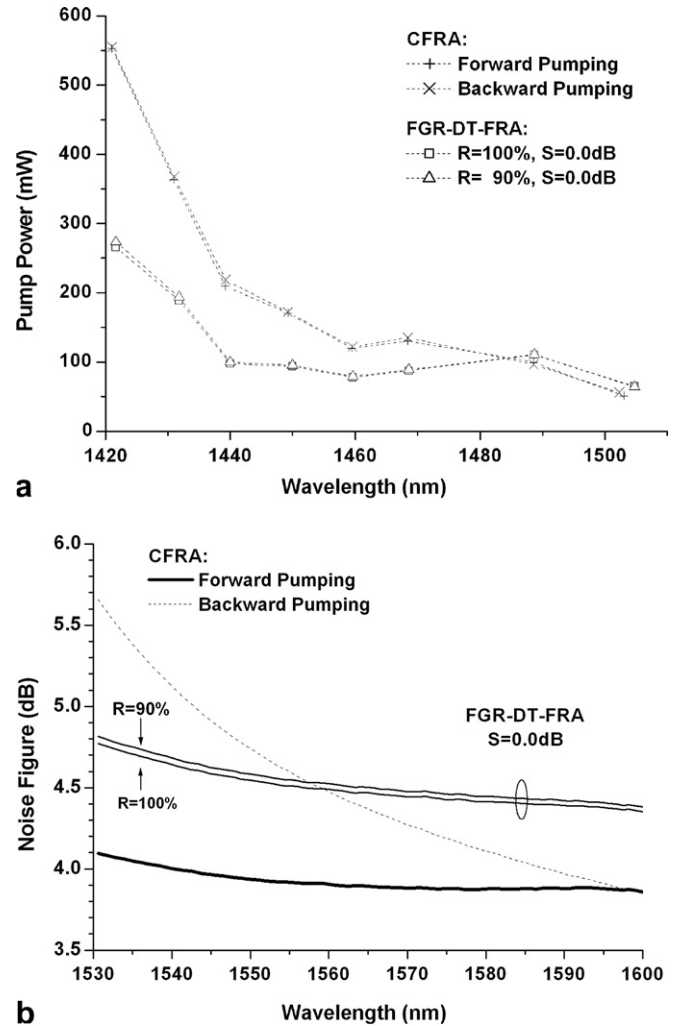


Fig. 2. (a) Pump power spectra. (b) Noise figures of CFRAs and the FGR-DT-FRAs without splice loss, in which, cases with FGR reflectivity $R = 90\%$ and 100% for the FGR-DT-FRAs using forward pumping are shown. The cases of the CFRAs using forward and backward pumping are also shown for comparison.

higher because the signals doubly pass the high-gain amplifying medium. For the FGR-DT-FRA, the power penalty due to 90% FGR reflectivity is only 19 mW. Fig. 3 shows the power evolution of the 1563.31 nm signal, which is reflected at 2.47 km, in the FGR-DT-FRAs with $R = 90\%$ and 100% . One can see that, for the FGR-DT-FRA with $R = 90\%$, the signal after reflection requires more gain than the case with $R = 100\%$ for obtaining 20 dB gain at the output of the amplifier. The transmit signal after FGR is still amplified by the pumps, but the pump depletion due to the transmit signal is little because the transmit signal power is low.

It is well known that the noise figure of the broadband CFRA using backward pumping increases as the signal wavelength decreases because the ASE around the short-wavelength signal is significantly amplified by the high-power short-wavelength pumps near the output end of the CFRA. For the CFRA using forward pumping, its noise figures are lower, but it suffers from the gain transients [13,14] which are not considered in this paper. Because the signals are reflected in the DCF of the FGR-DT-FRA, the noise performance of the FGR-DT-FRA should be between the CFRA using forward pumping and the CFRA using backward pumping. Fig. 2b shows the noise figures of the cases shown in Fig. 2a. One can see that the noise figure spectrum of the FGR-DT-FRA is as flat as the CFRA using forward pumping, but is about 0.57 dB higher in average. Compared with the case with $R = 100\%$, the noise figures of the FGR-DT-FRA with $R = 90\%$ are slightly increased. From the above results, the impacts of the FGR reflectivity on the pump powers and noise figures are little.

Next we consider the cases that the FGRs are inserted into the DCF by splicing. Owing to the advance of fusion splicer, typical splice loss for the DCFs of the same mode

field diameter can be less than 0.02 dB [15]. However the cases of higher splice loss are also shown in the following. Fig. 4a shows the pump power spectra of the FGR-DT-FRAs with the splice loss $S = 0$ dB, 0.01 dB, 0.02 dB, 0.03 dB, 0.04 dB, and 0.05 dB, in which the FGR reflectivity $R = 90\%$. Fig. 3 also shows the power evolution of the 1563.31 nm signal in the FGR-DT-FRAs with the splice loss $S = 0.05$ dB. Note that the first FGR, which reflects 1530.61 nm signal, is at 2.18 km. Comparing with the case without splice loss, one can see that the signal is amplified to a higher power level before 2.18 km. Then, the signal power is attenuated by the splice losses of the FGRs before and after reflection to within the region between 2.18 km and 2.47 km. As to the transmit signal after 2.47 km, its gain provided by pumps is not enough to compete with the splice losses of the FGRs and its power is still attenuated. Thus higher pump power is required for the case with splice loss. The total pump powers are 1006 mW, 1092 mW, 1180 mW, 1267 mW, 1353 mW, and 1439 mW for the cases of $S = 0$ dB, 0.01 dB, 0.02 dB, 0.03 dB, 0.04 dB, and 0.05 dB.

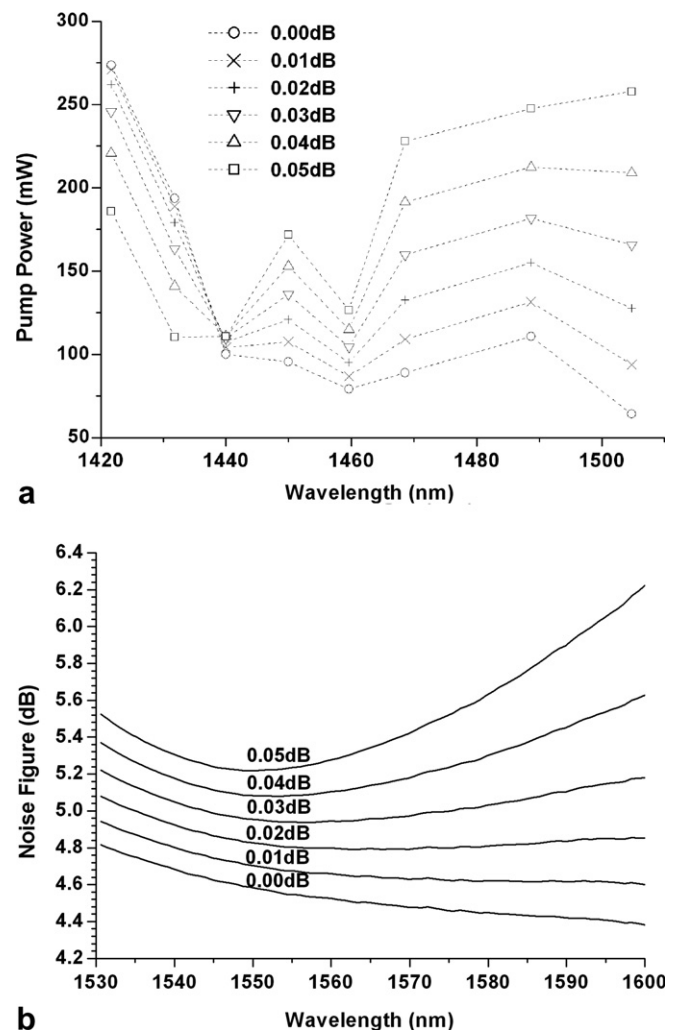


Fig. 3. Power evolution of the 1563.31 nm signal in the FGR-DT-FRAs without splice loss, in which, cases with FGR reflectivity $R = 90\%$ and 100% are shown. The case in the FGR-DT-FRA with the splice loss $S = 0.05$ dB for a splice point and the FGR reflectivity $R = 90\%$ is also shown. The input power is -23 dBm.

Fig. 4. (a) Pump power spectra. (b) Noise figures of the FGR-DT-FRAs with the splice loss $S = 0$ dB, 0.01 dB, 0.02 dB, 0.03 dB, 0.04 dB, and 0.05 dB for a splice point, in which the FGR reflectivity $R = 90\%$.

0.04 dB, and 0.05 dB, respectively. Note that the total pump power almost linearly increases with splice loss. The power penalty for the increment of 0.01 dB splice loss is about 86.6 mW. However, the required pump powers of the FGR-DT-FRAs are smaller than the CFRAs even for the case with the high splice loss of 0.05 dB. For the FGR-DT-FRAs with splice loss, the powers of their long-wavelength pumps, which are responsible for amplifying the long-wavelength signals, are increased because the long-wavelength signals travel deeper into the DCF and the accumulated splice losses experienced by the long-wavelength signals and pumps are higher. Fig. 4b shows the noise figures of the cases shown in Fig. 4a. The noise figures of the FGR-DT-FRA increase with splice loss because the ASEs are amplified by higher pump powers. From Fig. 4a, the increase of the noise figure at long wavelength due to splice loss is more than that at short wavelength, because the long-wavelength signal experiences more splice loss. On an average, the noise figure is increased by about 0.2 dB per 0.01 dB loss increment of a splice point. Therefore the splice loss should be kept as low as possible for the FGR-DT-FRA for saving pump powers and reducing noise figures.

4. Conclusions

DCF-based FGR-DT-FRA provides a degree of freedom to tailor the accumulated-dispersion spectra in the amplifier for the broadband WDM signal channels. For a specific system requirement, both its fiber loss and dispersion can be compensated as desired, with a commercially available DCF and without re-designing the index profile of the DCF, to meet the requirement. The amplifier compensates for the accumulated dispersions of 86 ITU 100 GHz-spaced WDM signal channels in 100 km True-Wave-RS fiber and provides 20 dB gain for each channel and is taken as an example. It is shown that the pump powers of the FGR-DT-FRA can be more efficiently utilized than that of the CFRA and its performance of noise figure including DRS is between the CFRA using forward pumping and the CFRA using backward pumping. The increases of required pump powers and noise figures, which are due to the reflectivity and splice loss of the FGR, are investi-

gated. The results show that the increments are not significant for the practical values of reflectivity and splice loss. The induced noise of the signal due to RIN of the pump lasers is not considered in this paper. Although the pump powers are forward launched for the FGR-DT-FRA, reflected signals are counter-pumped. The impact of the RIN of the pump lasers on the FGR-DT-FRA should be less than that on the CFRA using forward pumping and be larger than that on the CFRA using backward pumping.

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