Numerical comparison on the characteristics between backward and bi-directionally pumped DFRAs in hybrid Raman/EDFAs

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Received June 21, 2004

The characteristics of broadband backward and bi-directionally pumped distributed fiber Raman amplifiers (DFRAs) in hybrid Raman/erbium-doped fiber amplifiers (HFAs) configuration are compared numerically based on noise-nonlinear figure (NNF) when standard single mode fiber (SMF) and non-zero dispersion-shifted fiber (NZDSF) are considered. It is found that achievable NNF in optimized bi-directionally pumped HFAs is about 1.2 dB (or 1.7 dB) higher than that in backward pumped HFAs for SMF (or NZDSF), and better characteristics can be achieved by using NZDSF rather than SMF for long haul transmission.

OCIS codes: 060.2320, 060.2330.

For the passed years, distributed fiber Raman amplifier (DFRA) has been recognized as one of the key technologies in the high capacity, long haul dense wavelength division multiplexing (DWDM) optical fiber transmission systems because of its better noise performance, wide gain bandwidth (80—120 nm), and free operation wavelength range[1]. In early time, backward pumped distributed fiber Raman amplifier (B-DFRA) is widely used because the signal power fluctuation caused by pump relative intensity noise can be suppressed in such a structure. But in a broadband B-DFRA, the shorter wavelength signal channels suffer more noise deterioration due to the temperature-dependent noise, pump interaction, and signal-to-signal Raman scattering[2]. To reduce this wavelength related noise deterioration, bi-directional pumping configuration (Bi-DFRA) is proposed by moving parts of the shorter wavelength pump powers to the forward so that both flattened gain and noise profile can be achieved[3]. However, the path-average signal power in a Bi-DFRA is higher than that in B-DFRA, so Bi-DFRA faces to another serious problem that more nonlinearity is introduced[4]. As well known, not only the optical noise, but also the nonlinearity may degrade the system performance, so a question comes out: how much benefit can be achieved by using bi-directionally pump configuration?

To answer this question, a most direct way is to compare the bit error ratio (BER) of signals, but it is very time-consuming in simulation since a lot of calculations are required. Another convenient way is to compare the optical signal-to-noise ratio (OSNR) for considering optical noise and to compare the accumulated nonlinear phase shift for taking the nonlinear impairment into account[4−6]. Reference [6] proposes a new parameter of noise-nonlinear figure (NNF) for both optical noise and accumulated nonlinear phase shift simultaneously: $NNF(\lambda) = OSNR(\lambda)/\gamma\int_0^L P(\lambda,z)\mathrm{d}z$, where $OSNR(\lambda)$ and $\gamma\int_0^L P(\lambda,z)\mathrm{d}z$ represent OSNR and accumulated nonlinear phase shift for the signal channel at wavelength λ, respectively. Obviously, the physical meaning of NNF is the achievable OSNR in a unit Kerr nonlinear phase shift.

On the other hand, limited by available pump power and double Rayleigh scattering and also to avoid nonlinear impairment, DFRA usually operates at low gain with a followed erbium-doped fiber amplifier (EDFA) together to form so-called hybrid Raman/EDFAs (HFAs)[5], where the performance is related to both of DFRA and EDFA as well as the gain distribution between them. In this letter, the NNF between the individually optimized backward and bi-directionally pumped HFAs (B-HFAs and Bi-HFAs) is compared numerically on 100-km standard single mode fiber (SMF) and non-zero dispersion-shifted fiber (NZDSF). The results show that the reachable NNF for Bi-HFAs is about 1.2 dB (or 1.7 dB) higher than that for B-HFAs in single SMF (or NZDSF) span. It is also found that the resulted NNF on NZDSF are higher than those on SMF.

Figure 1 shows the arrangement of a single span in the long haul dispersion compensated wavelength division multiplexing (WDM) transmission system amplified by HFAs, where the transmission fiber is backward or bi-directionally pumped and followed by two EDFAs with dispersion compensation fiber (DCF) in between.

Let G_{E1} and NF_{E1} represent the gain and noise figure for EDFA1, G_{E2} and NF_{E2} for EDFA2, G_{RA} be the net gain for DFRA (including on-off gain and fiber loss), and NF_{RA} the noise figure corresponding to G_{RA}, then the noise-nonlinear figure for single span NNF_{span} at

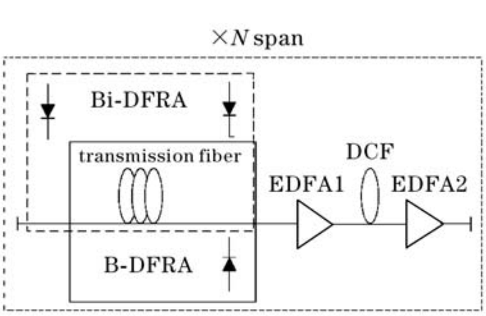

Fig. 1. The arrangement of a HFA span.

each wavelength can be derived from the definition in Ref. [6] that

$$NNF_{\mathrm{span}}(\lambda) = \{NF_{\mathrm{span}}(\lambda) \cdot (hcB_{\mathrm{o}}/\lambda) \cdot \left[\gamma L_{\mathrm{eff}}(\lambda) + \gamma_{\mathrm{DCF}} G_{\mathrm{RA}}(\lambda) G_{\mathrm{E1}}(\lambda) L_{\mathrm{eff}}^{\mathrm{DCF}}(\lambda)\right]\}^{-1}, \quad (1)$$

where $NF_{\mathrm{span}}(\lambda) = NF_{\mathrm{RA}} + \frac{1}{G_{\mathrm{RA}}} NF_{\mathrm{E1}} + \frac{\exp[-\alpha_{\mathrm{DCF}}(\lambda) \times L_{\mathrm{DCF}}]}{G_{\mathrm{RA}} G_{\mathrm{E1}}} NF_{\mathrm{E2}}$ is the noise figure for whole span, α_{DCF} is the attenuation coefficient for DCF. γ, γ_{DCF} and L_{eff}, $L_{\mathrm{eff}}^{\mathrm{DCF}}$ are the nonlinear coefficients and the effective lengths for the transmission fiber and DCF, respectively. h, c, and B_{o} are the Planck's constant, vacuum light speed, and the bandwidth for optical noise measurement, respectively.

To carry out the simulation investigation, SMF was taken as the transmission fiber and the span length was 100 km. The length of DCF can be determined by assuming that the DCF could be properly selected so that same degree of dispersion compensation $k_{cp} = -D_{\mathrm{DCF}} \cdot L_{\mathrm{DCF}}/D \cdot L$ would be achieved for all the channels. Here, D_{DCF}, D and L_{DCF}, L are fiber dispersion parameters and lengths for DCF and transmission fiber, respectively. By setting the compensating degree k_{cp} as 1, the length of DCF was calculated to be 20 km. All the fiber parameters were obtained from experiment, as shown in Table 1. Eighty WDM channels over C+L band (1529—1560.2 nm and 1572.2—1603.4 nm) with an interval of 0.8 nm were launched into the span. B_{o} was set as 12.5 GHz (0.1 nm). Five pump wavelengths at 1423, 1433, 1443, 1463, and 1493 nm were used to achieve about 75-nm flat gain for DFRA. In the Bi-DFRA case, only part of the power at the shorter four wavelengths was set forward to achieve both flat gain and flat noise figure profile.

The simulation was started from a pair of given net gain $G_{\mathrm{RA}}^{\mathrm{set}}$ and input channel power P_{TX}, the power for individual pump wavelength was calculated by employing the procedure similar as reported in Refs. [7] and [8] which was determined by flattening gain in B-DFRA and flatten both gain and noise figure profile in Bi-DFRA. After the pump combination was determined, $G_{\mathrm{RA}}(\lambda)$, $NF_{\mathrm{RA}}(\lambda)$, and $L_{\mathrm{eff}}(\lambda)$ for DFRA as well as the accumulated nonlinear phase shift ϕ_{NL} over the transmission fiber for each channel were obtained by solving the coupling equation set[9]. Figures 2(a) and (b) show the results of optimized $G_{\mathrm{RA}}(\lambda)$, corresponding $NF_{\mathrm{RA}}(\lambda)$ and ϕ_{NL} for B-DFRA and Bi-DFRA for the given $G_{\mathrm{RA}}^{\mathrm{set}} = -10$ dB and $P_{\mathrm{TX}} = -3$ dBm. It can be seen that for Bi-DFRA, NF_{RA} value at shorter wavelengths is much improved but ϕ_{NL} is also higher as expected.

After the gain of DFRA $G_{\mathrm{RA}}(\lambda)$ was obtained, the total gain for the two EDFAs can be easily determined as $G_{\mathrm{E1}} + G_{\mathrm{E2}} = \alpha_{\mathrm{DCF}} L_{\mathrm{DCF}} - G_{\mathrm{RA}}$ (dB). If the losses of transmission fiber and DCF were compensated completely, then only one gain between EDFA1 and EDFA2 is independent, so a ratio of $\eta = G_{\mathrm{E1}}/(G_{\mathrm{E1}} + G_{\mathrm{E2}})$ can be used as a designable parameter. On the other hand, NF of an EDFA can be optimized independent of its gain for all signal channels, so both NF_{E1} and NF_{E2} can be assumed reasonably to be 4.5 dB. Then, for any set of given $G_{\mathrm{RA}}^{\mathrm{set}}$ and η, $NNF_{\mathrm{span}}(\lambda)$ at each channel can be found out. Usually, the performance of the worst channel is used to evaluate a WDM transmission system. Figure 3 shows the calculated lowest channel's NNF_{span} versus G_{RA} (from -10 dB to 0) and η (from 0 to 1) with fixed $P_{\mathrm{TX}} = -3$ dBm for B-HFAs and Bi-HFAs, respectively.

The results show that in the higher η area, NNF_{span} decreases with increasing η because higher gain of EDFA1 leads to higher power in DCF fiber, and the induced higher nonlinear phase shift would lower NNF_{span}.

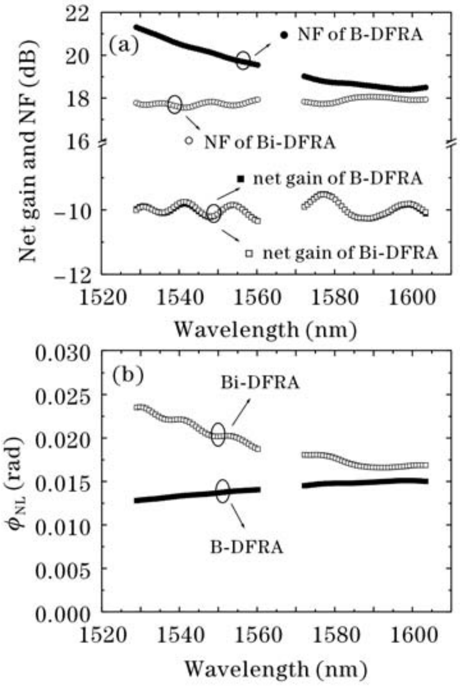

Fig. 2. Numerical simulation spectra of NF and net gain (a) and nonlinear phase shift (ϕ_{NL}) (b) for B-DFRA (solid) and Bi-DFRA (open) with $G_{\mathrm{RA}}^{\mathrm{set}} = -10$ dB on 100-km SMF.

Table 1. Experimental Parameters

Fiber Type	Peak Raman Gain Coefficient (W/km)	Nonlinear Coefficient (W/km)	Attenuation Coefficient at 1550 nm (dB/km)	Dispersion Coefficient (ps/(nm·km))	Rayleigh Scattering Coefficient (dB/km)
SMF	0.39	1.2	0.2	17	−40
DCF for SMF	1.25	5.7	0.42	−85	—
NZDSF	0.554	1.9	0.22	4.5	−38
DCF for NZDSF	1.25	5.7	0.42	−91	—

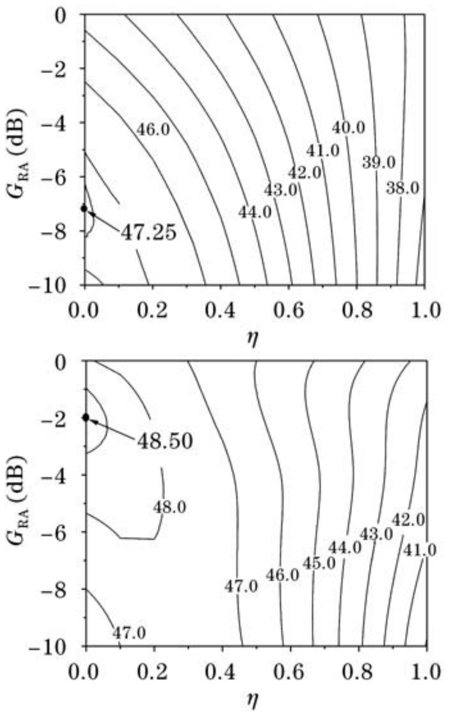

Fig. 3. The calculated contour map of lowest channel's NNF_{span} (dB) (shown on the curves) versus net gain of DFRA (G_{RA}) and gain ratio of EDFA1 (η) for B-HFAs (a) and Bi-HFAs (b) on 100-km SMF.

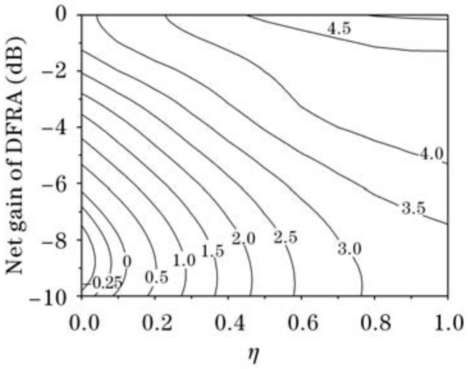

Fig. 4. The calculated contour map of $\Delta NNF_{\mathrm{span}}$ (dB) (shown on the curves) between Bi-HFAs and B-HFAs versus net gain of DFRA and gain ratio of EDFA1 (η) on 100-km SMF.

While in the low η area, NNF_{span} is more dependent on G_{RA}. OSNR can be improved by the higher forepart gain until the nonlinear phase shift becomes dominant, so there is an optimized gain arrangement with best NNF_{span}, which is 47.25 dB at $\eta = 0$, $G_{\mathrm{RA}} = -7.2$ dB for B-HFAs and 48.5 dB at $\eta = 0$, $G_{RA} = -2$ dB for Bi-HFAs, respectively. The best NNF_{span} for Bi-HFAs appears at higher G_{RA}, because the bi-directional pump improves more in NF for the worst channel and thus more margin is left. Figure 4 shows the difference of lowest channel NNF_{span} by subtracting the B-HFAs value from that of the Bi-HFAs at the same G_{RA} and η. For high G_{RA} and η, the benefit from Bi-HFAs can be up to 4.5 dB, while at the lowest G_{RA} and η, $\Delta NNF_{\mathrm{span}}$ is even minus, because the total gain before DCF is not enough to improve the OSNR and the disadvantage of more nonlinear phase shift in Bi-HFAs even lowers the NNF. Practically, one should compare the characteristics between the B-DFRA and Bi-DFRA based on individually optimized results then only 1.25-dB benefit is achievable (48.50 dB versus 47.25 dB).

Intuitively, NNF_{span} and the optimized design of HFAs are related to the channel's power P_{TX}, but higher channel's power would create not only higher OSNR but also higher nonlinearity so that the total effects on NNF_{span} may be counteracted. Signal-to-signal scattering (SSRS) is noticeable only when signal power is high. Our further simulation confirmed that the NNF_{span} data are almost independent of P_{TX} within the range from −20 to 1 dBm (at $G_{\mathrm{RA}} = -4$ dB and $\eta = 0$). In long haul transmission system, the input signal power is usually low to avoid significant nonlinearity, so P_{TX} can be approximately treated as of no influence on NNF_{span}.

To know more about the achievable benefit from Bi-HFAs, cascaded systems employing B-HFAs and Bi-HFAs are also considered. The total NNF after N spans transmission is given by

$$NNF_{\mathrm{tot}}(\lambda) = \frac{OSNR_{\mathrm{tot}}}{\phi_{\mathrm{tot}}} = \frac{1}{N^2} \cdot \frac{OSNR_{\mathrm{span}}}{\phi_{\mathrm{span}}} = \frac{1}{N^2} \cdot NNF_{\mathrm{span}}(\lambda), \tag{2}$$

which means that the NNF difference between the systems employing B-HFAs and Bi-HFAs will be the same as in single span if their span number are same. For given tolerable minimum $OSNR_{\mathrm{min}}$ and maximum $\phi_{\mathrm{NL\,max}}$ at receiver, the allowable span number N_{max} can be derived from Eq. (2) as[5]

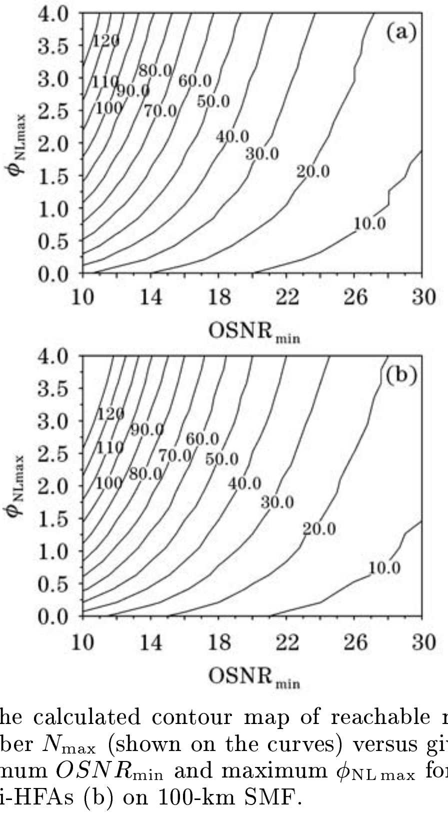

Fig. 5. The calculated contour map of reachable maximum span number N_{max} (shown on the curves) versus given tolerable minimum $OSNR_{\mathrm{min}}$ and maximum $\phi_{\mathrm{NL\,max}}$ for B-HFAs (a) and Bi-HFAs (b) on 100-km SMF.

$$N_{\max} = \mathrm{int}\left[\sqrt{NNF_{\mathrm{span}} \cdot \frac{\phi_{\mathrm{NL\,max}}}{OSNR_{\min}}}\right]. \qquad (3)$$

Figure 5 shows the calculated span number over the range of $OSNR_{\min} = 10 - 30$ dB and $\phi_{\mathrm{NL\,max}} = 0.1 - 4$ rad for B-HFAs and Bi-HFAs respectively, where the same span parameters and optimized NNF_{span} as shown in Fig. 3 were used.

For example, when $OSNR_{\min} = 20$ dB and $\phi_{\mathrm{NL\,max}} = 1.8$ rad, $N_{\max}$ is 30 for B-HFAs and 34 for Bi-HFAs. It means that the system with Bi-HFAs can reach 400 km more transmission distance than that with B-HFAs.

Similar comparisons between B-HFAs and Bi-HFAs were also carried out on a 100-km NZDSF span. The fiber parameters for NZDSF were also obtained from experiment, shown also in Table 1. The same pump wavelengths, signal wavelengths, and noise figure of EDFAs as those in Fig. 3 were adopted. The input channel's power was fixed at $P_{\mathrm{TX}} = -6$ dBm. The dispersion of corresponding DCF is −91 ps/(nm·km) and then the length of DCF is calculated to be 5 km with $k_{cp} = 1$. The results show that, the best NNF_{span} value is 48.36 dB for B-HFAs at $G_{\mathrm{RA}} = -7$ dB, $\eta = 0$, and 50.03 dB for Bi-HFAs at $G_{\mathrm{RA}} = -1$ dB, $\eta = 0$, respectively. Compared with the data on SMF, about 1.1 dB (1.4 dB) improvement is achieved for B-HFAs (Bi-HFAs). The benefit from Bi-HFAs is about 1.7 dB, which is also higher than that in SMF. The improvement mainly comes from much shorter DCF fiber length (5 km versus 20 km), which can reduce much of the span nonlinearity and loss. It is worth to note that, the optimized G_{RA} on NZDSF are at the same level as on SMF, implying the gain from EDFAs is lowered, so that more advantage of DFRA for improving OSNR is taken and the noise power from EDFAs is reduced. These results indicate that NZDSF is more suitable for long haul transmission.

In conclusion, the performances between the backward and bi-directionally pumped HFA spans based on 100-km SMF and NZDSF are compared numerically with respect to the worst channel NNF. The reachable NNF for Bi-HFAs is about 1.2 dB (or 1.7 dB) higher than that for B-HFAs in single SMF (or NZDSF) span when the spans are optimized individually. For cascaded 100-km-span SMF system, about 13% longer transmission distance (3400 km versus 3000 km) can be achieved by Bi-HFAs. More benefit may be achieved by using NZDSF for long haul transmission since DCF length is much shorter.

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