Gain and Noise Figure Spectrum Control Algorithm for Fiber Raman Amplifiers

Jaehyoung Park, *Student Member, IEEE*, Jonghan Park, *Student Member, IEEE*, Pilhan Kim, *Student Member, IEEE*, and Namkyoo Park, *Member, IEEE*

***Abstract*—In this letter, a fiber Raman amplifier (FRA) design method enabling the simultaneous control of the gain and noise figure (NF) spectra, is proposed. By constructing the FRA with predetermined target forward/backward gain spectra, the spectral error function of NF is calculated, to determine the pump power combination satisfying both the targeting gain and NF spectra. The FRA gain/NF design within 0.1 dB of accuracy is demonstrated for various shapes of target spectra.**

***Index Terms*—Fiber Raman amplifiers (FRAs), iterative method, modeling, noise figure (NF), optimization method.**

I. Introduction

FOR multichannel optical transmission systems, the channel with the worst optical signal-to-noise ratio usually determines the overall system penalty. The uniformity in the noise figure (NF) and the gain flatness in this sense represent two key factors that should be considered in the first step of designing amplified wavelength-division-multiplexed systems. In the case of fiber Raman amplifier (FRA), the shortest wavelength channel usually experiences the worst NF performances due to the pump depletion effect and higher fiber attenuations at the shortest pump wavelength. Serious efforts have been made in the past to avoid this problem using a bidirectional [1], [2], higher order [3], time-multiplexed [4] pumping method, or employing post gain tilt compensation [5].

Of these approaches, due to the inherent benefit of reduced NF and reduced hardware complexity, bidirectional pumping has generally been considered as the most promising solution. Even though in principle it is well understood that NF control under a fixed gain spectrum can be made with proper adjustment of the forward/backward pumping ratio [1], there has not been any report for systematically formulating/describing the intuitively correct optimization algorithm. As one of the possible resolution, a genetic algorithm was also used to *select the best result out of multiple ab initio pumping scenarios* [2]. However, the obtained solution was only near-optimal with increased computation cost requiring N times solving problems for N pumping scenarios.

This letter proposes an efficient method for simultaneous and precise *design* of the spectra both for the gain and NF of depleted/undepleted FRA. First constructing the FRA with target gain spectrum and then taking the NF spectral error function (between the target NF spectrum and NF spectrum from the initial FRA design) as a feedback parameter in order to adjust the forward/backward pumping ratio, precise (<0.1 dB) and fast (~10 s with 2-GHz desktop) engineering of FRA gain/NF spectra is achieved.

Manuscript received November 11, 2005; revised March 2, 2006.

The authors are with Optical Communication Systems Laboratory, School of Electrical Engineering and Computer Sciences, Seoul National University, Seoul 151-744, Korea (e-mail: nkpark@snu.ac.kr).

Digital Object Identifier 10.1109/LPT.2006.873927

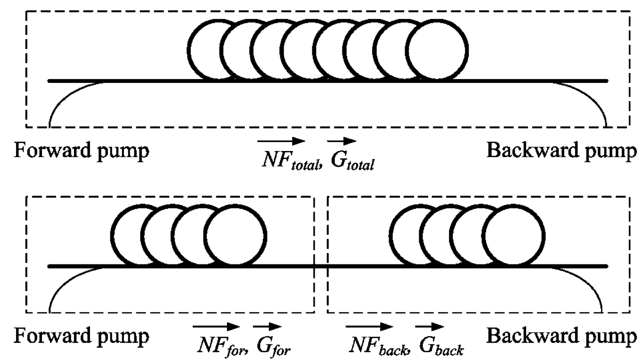

Fig. 1. Conceptual drawing for the construction of the design algorithm: distributed FRA and its equivalent, cascaded two-stage FRA.

II. Theory

For the development of the algorithm, we start with a bidirectionally pumped, distributed FRA which can be considered *in effect and in good approximation* as a cascaded, forward-pumped, and backward-pumped FRA (Fig. 1). The NF of the composite FRA, including the fiber loss, can then be written as

$$\begin{aligned}\overrightarrow{\mathrm{NF}}_{\mathrm{total}} &= \overrightarrow{\mathrm{NF}}_{\mathrm{for}} + \frac{\overrightarrow{\mathrm{NF}}_{\mathrm{back}} - 1}{\vec{G}_{\mathrm{for}}} \\ &= \overrightarrow{\mathrm{NF}}_{\mathrm{for}} + \frac{\overrightarrow{\mathrm{NF}}_{\mathrm{back}} - 1}{\vec{G}_{\mathrm{total}}} \cdot \vec{G}_{\mathrm{back}} \end{aligned} \tag{1}$$

where $\overrightarrow{\mathrm{NF}}$ and $\vec{G}$ is the NF and gain spectrum vector (in wavelength number). For the predetermined target gain value $\vec{G}_{\mathrm{total}}$ to achieve the target $\overrightarrow{\mathrm{NF}}_{\mathrm{total}}$ spectrum, the adjustment in forward/backward NF ($\overrightarrow{\mathrm{NF}}_{\mathrm{for}}$, $\overrightarrow{\mathrm{NF}}_{\mathrm{back}}$) and backward (or equivalently second stage) gain $\vec{G}_{\mathrm{back}}$ is required under this formulation. Also important to note, most of variations in $\overrightarrow{\mathrm{NF}}_{\mathrm{total}}$ comes from $\vec{G}_{\mathrm{back}}$ when $\vec{G}_{\mathrm{total}}$ is fixed. The changes in $\overrightarrow{\mathrm{NF}}_{\mathrm{for}}$ and $\overrightarrow{\mathrm{NF}}_{\mathrm{back}}$, therefore, are almost negligible, as can be seen in Fig. 2.

1041-1135/$20.00 © 2006 IEEE

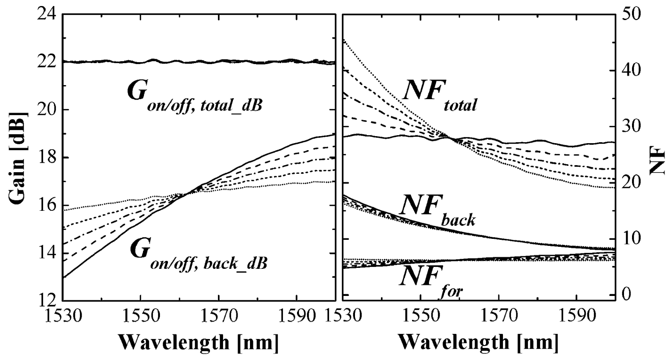

Fig. 2. Total, backward, and forward NF for various backward gain values (under the identical total gain of 22 dB).

Based on above observations, (1) is rearranged to obtain the expression for the *target* backward gain $\vec{G}^{\text{target}}_{\text{back\_dB}}$ under the given target gain and NF spectra ($\vec{G}^{\text{target}}_{\text{total\_dB}}$, $\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}}$)

$$\vec{G}^{\text{target}}_{\text{back\_dB}} = 10 \cdot \log_{10}\left(\frac{\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}} - \overrightarrow{\text{NF}}^{\text{target}}_{\text{for}}}{\overrightarrow{\text{NF}}^{\text{target}}_{\text{back}} - 1}\right) + \vec{G}^{\text{target}}_{\text{total\_dB}}. \tag{2}$$

In order to determine $\vec{G}^{\text{target}}_{\text{back\_dB}}$, we need to know $\overrightarrow{\text{NF}}^{\text{target}}_{\text{for}}$ and $\overrightarrow{\text{NF}}^{\text{target}}_{\text{back}}$ (unknown at this point), which can be obtained only at the final stage of the design. Instead, here we utilize the gain and NF spectra values which can easily be obtained from the FRA solution of a known structure, for example, with a predetermined forward/backward gain. For this case, (2) can be written as $(\text{index } (k) = \text{known})$

$$\vec{G}^{(k)}_{\text{back\_dB}} = 10 \cdot \log_{10}\left(\frac{\overrightarrow{\text{NF}}^{(k)}_{\text{total}} - \overrightarrow{\text{NF}}^{(k)}_{\text{for}}}{\overrightarrow{\text{NF}}^{(k)}_{\text{back}} - 1}\right) + \vec{G}^{\text{target}}_{\text{total\_dB}}. \tag{3}$$

Now, taking the difference between (2) and (3), meanwhile using an approximation of $\overrightarrow{\text{NF}}^{\text{target}}_{\text{for/back}} \approx \overrightarrow{\text{NF}}^{(k)}_{\text{for/back}}$ (justified in the discussion related to Fig. 2), it is possible to get the expression for the amount of backward gain adjustment $\Delta\vec{G}^{(k)}_{\text{back\_dB}}$ required to achieve the target NF spectra $\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}}$ as well as the target gain $\vec{G}^{\text{target}}_{\text{total\_dB}}$

$$\begin{aligned}\Delta\vec{G}^{(k)}_{\text{back\_dB}} &= \vec{G}^{\text{target}}_{\text{back\_dB}} - \vec{G}^{(k)}_{\text{back\_dB}} \\ &\cong 10 \cdot \log_{10}\left(\frac{\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}} - \overrightarrow{\text{NF}}^{(k)}_{\text{for}}}{\overrightarrow{\text{NF}}^{(k)}_{\text{total}} - \overrightarrow{\text{NF}}^{(k)}_{\text{for}}}\right).\end{aligned} \tag{4}$$

It is worth noting that, as offset could exist between $\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}}$ and $\overrightarrow{\text{NF}}^{(k)}_{\text{total}}$ from the pump reconfiguration, in the practical implementation of the algorithm, the target NF $\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}}$ is obtained by adding $\text{mean}_{\text{spectral}}(\overrightarrow{\text{NF}}^{(k)}_{\text{total}})$ and $\text{tilt}(\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}})$. $\text{tilt}(\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}})$ is the spectral variation of the target NF from its mean value $\text{mean}_{\text{spectral}}(\overrightarrow{\text{NF}}^{(k)}_{\text{total}})$. Furthermore, because an approximation $\overrightarrow{\text{NF}}^{\text{target}}_{\text{for/back}} \approx \overrightarrow{\text{NF}}^{(k)}_{\text{for/back}}$ has been used in deriving the above expression, we note here that (4) has to be applied in an iterative manner in order to achieve convergence satisfying the final design.

III. Implementation

For practical implementation of the theory developed with an ideal, cascaded two-stage FRA model, we start from the following equation modified from the references [6], [7]. Dividing the forward and backward pump part, we write

$$\vec{G}_{\text{total\_dB}} = \widetilde{T}_{P\_\text{back}} \cdot \vec{P}_{P\_\text{back}} + \widetilde{T}_{P\_\text{for}} \cdot \vec{P}_{P\_\text{for}} + \widetilde{T}_S \cdot \vec{P}_S \tag{5}$$

where $\vec{G}_{\text{total\_dB}}$ is the gain spectrum vector, and $\vec{P}_{P\_\text{back}}$, $\vec{P}_{P\_\text{for}}$, and $\vec{P}_S$ are the $M \times 1$, $M \times 1$, and $N \times 1$ power vector of the M forward pumps, M backward pumps, and N signals, respectively. Note that $\widetilde{T}_{P\_\text{back}}$, $\widetilde{T}_{P\_\text{for}}$, and $\widetilde{T}_S$ are $N \times M$, $N \times M$, and $N \times N$ transfer matrices, composed of the products of gain coefficients and effective lengths—relating forward, backward pumps, and neighbor channel signals to the signal gain (detailed expressions in [6] and [7]).

The following steps describe the practical algorithm used to find optimal forward/backward pump sets for the target gain/NF, under the above formulation.

Step 0: Set the target gain profile of FRA $\vec{G}^{\text{target}}_{\text{total\_dB}}$ and determine $\vec{G}^{(0)}_{P\_\text{back\_dB}}$ of backward-pumped FRA—one can set, for example, $\vec{G}^{(0)}_{P\_\text{back\_dB}} = r\vec{G}^{\text{target}}_{\text{total\_dB}}$ (r: ratio between backward gain/total gain).

Step I: Solving (5) in terms of $\vec{P}_{P\_\text{back}}$ with $\vec{P}_{P\_\text{for}} = 0$

$$\vec{P}^{(n)}_{P\_\text{back}} = (\widetilde{T}_{P\_\text{back}})^{-1} \cdot \left(\vec{G}^{(n)}_{P\_\text{back\_dB}} - \widetilde{T}_S \cdot \vec{P}_S\right), \quad \text{for } \vec{P}_{P\_\text{for}} = \vec{0}. \tag{6}$$

Backward pump powers $\vec{P}^{(0)}_{P\_\text{back}}$ is obtained, satisfying the backward target gain $\vec{G}^{(0)}_{P\_\text{back\_dB}}$. In addition, calculating $\vec{P}^{(0)}_{P\_\text{for}}$ with (5) and $\vec{P}^{(0)}_{P\_\text{back}}$

$$\vec{P}^{(n)}_{P\_\text{for}} = (\widetilde{T}_{P\_\text{for}})^{-1} \cdot \left(\vec{G}^{\text{target}}_{\text{total\_dB}} - \widetilde{T}_{P\_\text{back}} \cdot \vec{P}^{(n)}_{P\_\text{back}} - \widetilde{T}_S \cdot \vec{P}_S\right). \tag{7}$$

Forward pump powers $\vec{P}^{(0)}_{P\_\text{for}}$ is obtained, satisfying the final (total) target gain spectrum $\vec{G}^{\text{target}}_{\text{total\_dB}}$.

Step II: Using $\vec{P}^{(0)}_{P\_\text{for}}$, $\vec{P}^{(0)}_{P\_\text{back}}$, and the signal power evolutions in the FRA, it is possible to calculate the NF values, $\overrightarrow{\text{NF}}^{(0)}_{\text{for/total}}$ (eq. 15 and 31 in [8]). The obtained NF and NF tilt values are then compensated by backward FRA gain $\vec{G}^{(1)}_{P\_\text{back\_dB}}$ using $\Delta\vec{G}^{(0)}_{\text{back\_dB}}$ from (4).

Step III: Repeat Steps I and II to obtain the n^{th} backward pumping gain $\vec{G}^{(n)}_{P\_\text{back\_dB}}$—until $\Delta\vec{G}^{(n)}_{\text{back\_dB}}$ becomes a sufficiently small vector in order to meet both the target gain spectrum $\vec{G}^{\text{target}}_{\text{total\_dB}}$ and target NF spectrum $\overrightarrow{\text{NF}}^{\text{target}}_{\text{total}}$.

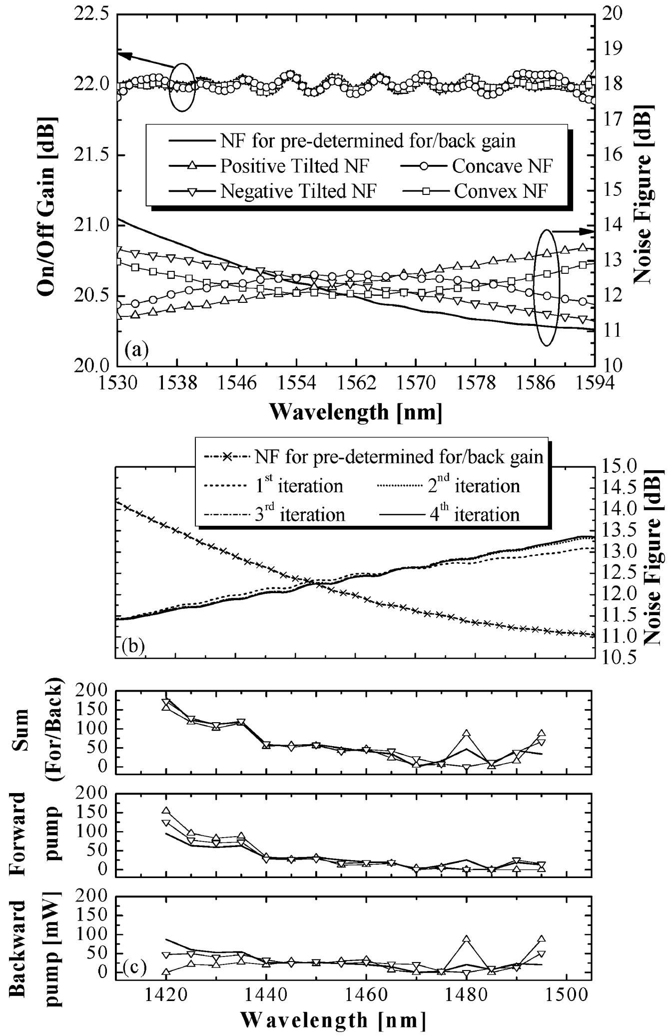

Fig. 3. FRA design (100-km DSF, $P_S = -5$ dBm/ch, 22-dB ON–OFF gain, $r = 0.6$). (a) NF achieved for different target spectra. (b) NF profiles at different stages of iteration. (c) Pump powers required for initial setting (solid line), and final stage of the NF design $(+/-\text{ tilt}: \Delta/\nabla)$.

IV. Application Examples

Numerical analysis was carried out on an FRA composed of 100-km dispersion-shifted fiber (DSF) with 22-dB flat ON–OFF gain. Eighty-one signals (-5 dBm/ch, 100-GHz spacing from 1530 to 1594 nm) and 5-nm equally spaced pumps (1420–1495 nm) were assumed as an example. Fig. 3(a) shows various NF spectra profiles attained with the initial design using $r = \vec{G}^{\text{target}}_{\text{back\_dB}}/\vec{G}^{\text{target}}_{\text{total\_dB}} = 0.6$ (line without symbol), and at the final stages of the design (after five iterations).

Excellent spectrum control (<0.1-dB error for gain and NF) was obtained with less than ~10-s computation time using a typical desktop (2 GHz).

To also test the feasibility of applying the proposed algorithm (originally developed for a distributed FRA) into the pump-depleted discrete FRA in the saturation regime, we constructed a dispersion-compensating FRA (DCF 10 km) with higher net gain (10 dB, ON–OFF gain $=$ 16 dB, -6 dBm/ch). Although an increased number of iterations (~15) was required, excellent control in the gain/NF spectrum (gain/NF error < 0.05 dB$/0.01$ dB) was achieved again, as shown in Fig. 4.

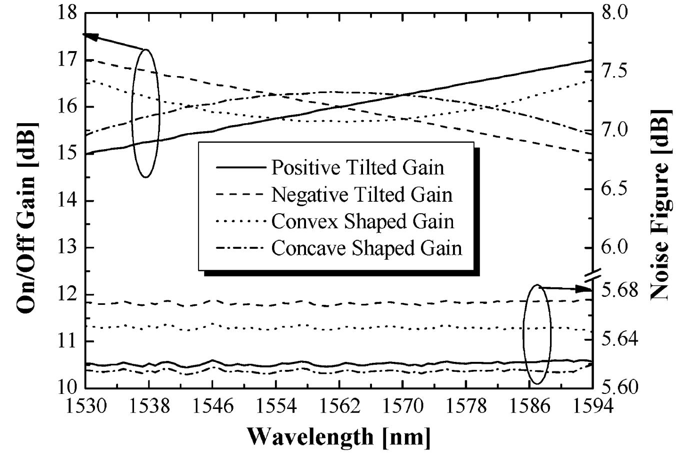

Fig. 4. Various gain shapes of a discrete FRA in the depletion regime (10-km DCF, $P_S = -6$ dBm/ch, $r = 0.7$), designed for flattened NF (pump wavelengths are identical to Fig. 3.).

V. Conclusion

For the first time, we have proposed a fast and efficient design algorithm for FRAs, enabling the control of both the gain and NF spectral shape.

We also have successfully demonstrated fast and precise construction of the FRA design for various target gain/NF profiles—providing additional degrees of freedom in the optimal design of FRAs and FRA-based transmission links.

References

[1] Y. Emori, S. Kado, and S. Namiki, "Broadband flat-gain and low-noise Raman amplifiers pumped by wavelength-multiplexed high-power laser diodes," *Opt. Fiber Technol.*, vol. 8, no. 2, pp. 107–122, Apr. 2002.
[2] X. Liu, J. Chen, C. Lu, and X. Zhou, "Optimizing gain profile and noise performance for distributed fiber Raman amplifiers," *Opt. Express*, vol. 12, no. 24, pp. 6053–6066, Nov. 2004.
[3] Y. Hadjar, N. J. Traynor, and S. Gray, "Noise figure tilt reduction in ultrawide-band WDM through second-order Raman amplification," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1200–1202, Apr. 2004.
[4] C. R. S. Fludger, V. Handerek, and N. Jolley, "Novel ultra-broadband high performance distributed Raman amplifier employing pump modulation," in *Optical Fiber Communications Tech. Dig. (OFC 2002)*, Mar. 2002, Paper WB4, pp. 183–184.
[5] X. Zhou and M. Birk, "New design method for a WDM system employing broadband Raman amplification," *IEEE Photon. Technol. Lett.*, vol. 16, no. 3, pp. 912–914, Mar. 2004.
[6] J. Park, P. Kim, J. Park, H. Lee, and N. Park, "Closed integral form expansion of Raman equation for efficient gain optimization process," *IEEE Photon. Technol. Lett.*, vol. 16, no. 7, pp. 1649–1651, Jul. 2004.
[7] N. Park, P. Kim, J. Park, and L. K. Choi, "Integral form expansion of fiber Raman amplifier problem," *Opt. Fiber Technol.*, vol. 11, pp. 111–130, Apr. 2005.
[8] I. P. Kaminow and T. Li, *Optical Fiber Telecommunications IVA*. New York: Academic, 2002, ch. 5, pp. 224–230.