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Parameters optimization of high efficiency discrete Raman fiber amplifier by using the coupled steady-state equations

Liang Dou [a], Shien-Kuei Liaw [b,*], Ming Li [a], Yi-Tseng Lin [b], Anshi Xu [a]

[a] *Department of Electronics, Peking University, Beijing 100871, China*
[b] *Department of Electronic Engineering, National Taiwan University of Science and Technology, No. 43, Sec. 4, Keelung Road, Taipei 106, Taiwan*

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Abstract

By using the coupled steady-state equations, we have numerically studied the characteristics optimization of Raman fiber amplifier (RFA) in a signal/pump double-passes-the-gain-medium scheme. The simulation results are in very good agreement with those of experimental data. Given a constant pumping power, the length of dispersion compensation fiber (DCF) in a RFA could be determined. The optimum design shows that the best length of the DCF is at around 3.8 ± 0.2 km in our study. This could provide both the highest signal output power and the lowest noise figure among all conditions we choose.

Keywords: Raman fiber amplifiers; Coupled steady-state equations; Dispersion compensation fiber; Double pass

1. Introduction

Raman fiber amplifiers (RFAs) have become increasingly important in optical communication systems and optical networks to compensate for the fiber loss and/or splitting loss. Comparing to the conventional rare-earth doped fiber amplifiers, RFAs have flexible signal gain band and low noise figure (NF) level [1]. Several system experiments demonstrated the benefits of Raman amplification including repeater-less undersea experiments [2], high-capacity terrestrial [3], submarine system transmission [4], shorter span single-channel system [5] and soliton system [6]. However, the pump efficiency of the conventional RFA is low when compared to that of the conventional erbium doped fiber amplifier (EDFA) [7]. Recently, we reported an RFA with signal/pump double-passes-the-gain-medium scheme by utilizing an optical circulator (OC) as a signal/pump reflector [8]. The pump efficiency improvement and the NF suppression can be realized simultaneously. Although it is crucial to numerically predict the characteristics of RFA such as signal power and NF versus pump wavelength, pump power, gain medium characteristic and so on, the optimum design of RFA parameters has not yet been addressed. In this paper, we preliminary describe the numerical simulation method to estimate the characteristics of signal/pump double-pass RFA, and then we verify the simulation results with the experimental data in [8] to confirm if they are closely matched with each other. Finally, we conclude that the optimized length of the dispersion compensation fiber (DCF), under a certain pump power and pump wavelength, could be predicted to get the largest output signal power and the lowest NF.

2. Theory and simulation

Fig. 1 depicts the similar configuration of RFA which has signal/pump power dual-passed the gain medium in [8]. Here, the Raman pump laser is launched into the dispersion compensation module (DCM) via a wavelength division multiplexing (WDM) coupler. The OC 2 in

* Corresponding author. Tel.: +886 2 2737 6384; fax: +886 2 2737 6424.
E-mail address: skliaw@mail.ntust.edu.tw (S.-K. Liaw).

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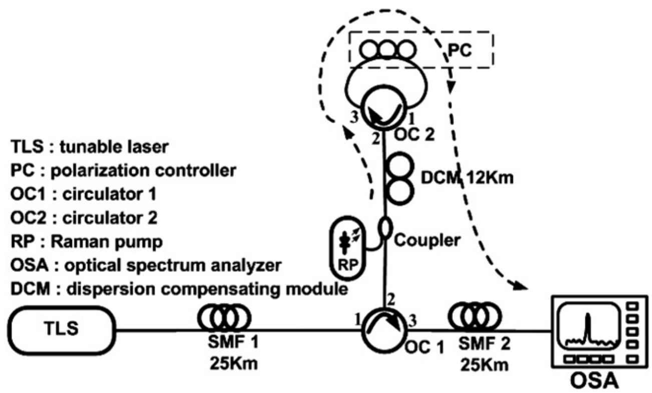

Fig. 1. Configuration of the RFA is depicted to have signal/pump power dual-pass the gain medium as shown in [8].

Fig. 1 is utilized as a reflected mirror both for the signal and pump laser to loop back into the DCM. The signal comes into port 2 of the OC 2, then travels from port 3 to port 1 via the connecting point, and then comes back to port 2. In such a configuration, signal and the Raman pump power double pass the DCM. While the DCM acts as a gain medium as well as a dispersion compensator. The residual pump laser in DCM is in counter direction with the incoming signal beam and hence increases the Raman gain. Without loss of generality, the Raman laser we used is lasing at 1495 nm. The experiments have successfully confirmed the pumping efficiency improvement for this kind of RFA is more efficiency than other types of RFAs. In such a signal/pump double-passed scheme, the analysis of signal round-trip propagation in the DCM is essential to predict RFA performance under various conditions. The method we use in simulation is based on a set of coupled steady-state equations that include spontaneous Raman emission and its temperature dependence, Rayleigh scattering, amplified spontaneous emission (ASE), stimulated Raman scattering (SRS), and arbitrary interaction between the pump laser and signals. The forward and backward power evolution of pump power, signals and ASE can be expressed in terms of the following equations [9].

$$\begin{aligned}\frac{\mathrm{d}P^{\pm}(z,v_{\mathrm{i}})}{\mathrm{d}z} &= \mp\alpha(v_{\mathrm{i}})P^{\pm}(z,v_{\mathrm{i}}) \pm \eta(v_{\mathrm{i}})P^{\mp}(z,v_{\mathrm{i}}) \\ &\pm P^{\pm}(z,v_{\mathrm{i}})\sum_{m=1}^{i-1}\frac{g_{\mathrm{R}}(v_{\mathrm{m}}-v_{\mathrm{i}})}{\Gamma A_{\mathrm{eff}}}\left[P^{\pm}(z,v_{\mathrm{i}})+P^{\mp}(z,v_{\mathrm{i}})\right] \\ &\pm hv_{\mathrm{i}}\sum_{m=1}^{i=1}\frac{g_{\mathrm{R}}(v_{\mathrm{m}}-v_{\mathrm{i}})}{\Gamma A_{\mathrm{eff}}}\left[P^{\pm}(z,v_{\mathrm{i}})+P^{\mp}(z,v_{\mathrm{i}})\right] \\ &\times\left[1+\left(\mathrm{e}^{\frac{h(v_{\mathrm{m}}-v_{\mathrm{i}})}{kT}}-1\right)^{-1}\right]\Delta v \mp P^{\pm}(z,v_{\mathrm{i}}) \\ &\times\sum_{m=i+1}^{n}\frac{v_{\mathrm{i}}}{v_{\mathrm{m}}}\frac{g_{\mathrm{R}}(v_{\mathrm{i}}-v_{\mathrm{m}})}{\Gamma A_{\mathrm{eff}}}\left[P^{\pm}(z,v_{\mathrm{i}})+P^{\mp}(z,v_{\mathrm{i}})\right] \\ &\mp 2hv_{\mathrm{i}}P^{\pm}(z,v_{\mathrm{i}})\sum_{m=i+1}^{n}\frac{v_{\mathrm{i}}}{v_{\mathrm{m}}}\frac{g_{\mathrm{R}}(v_{\mathrm{i}}-v_{\mathrm{m}})}{\Gamma A_{\mathrm{eff}}} \\ &\times\left[1+\left(\mathrm{e}^{\frac{h(v_{\mathrm{i}}-v_{\mathrm{m}})}{kT}}-1\right)^{-1}\right]\Delta\mu, \qquad (1)\end{aligned}$$

where $P^{+}(z,v_{\mathrm{i}})$ and $P^{-}(z,v_{\mathrm{i}})$ are the optical power of the forward and the backward propagating waves within infinitesimal bandwidth around v_{i}, respectively. α, η, h, k and T are attenuation coefficient, Rayleigh backscattering coefficient, Plank's constant, Boltzmann constant and temperature, respectively; A_{eff} is the effective area of the optical fiber at frequency v_{m}, $g(v_{\mathrm{i}}-v_{\mathrm{m}})$ is Raman gain parameter at frequency v_{m} due to pump laser at frequency v_{m}, the factor Γ accounts for polarization randomization effect with the value lies between 1 and 2. In [10], it is reasonable to assume that the ASE level combines other noises is 30 dB lower than that of the input signal, so we may calculate the pump and the signal without considering the combined noise. Thus, Eq. (1) can be simplified as

$$\pm\frac{\mathrm{d}P_{\mathrm{i}}}{\mathrm{d}z}=\left[-\alpha_{\mathrm{i}}+\sum_{j=1}^{i-1}\frac{g_{\mathrm{R}}(v_j-v_{\mathrm{i}})}{\Gamma A_{\mathrm{eff}}}P_j-\sum_{j=i+1}^{m}\frac{v_{\mathrm{i}}}{v_j}\frac{g_{\mathrm{R}}(v_{\mathrm{i}}-v_j)}{\Gamma A_{\mathrm{eff}}}P_j\right]P_{\mathrm{i}},\quad (i=1,2,\ldots,m), \qquad (2)$$

Fig. 2 shows a simplified scheme to represent the signal/pump double-passed configuration in a RFA. Along the section of DCF, the four major players are the forward pump power, backward pump power, forward signal power and backward signal power. In order to apply the above equation, one must know the four power levels at one side. Unfortunately, only the forward pump power and the forward signal power at $z=0$, as well as reflection coefficient at the other end of $z=L$ are known. To solve this problem, distribution of the signal power and the pump power along the whole DCF is calculated base on the following procedures.

Firstly, the backward pump and the backward signal at $z=0$ are assumed to be zero. Then we calculate the equations above from $z=0$ to $z=L$. Since the forward signals and the backward signals are determined by the reflected ratios, the assumed backward signal power and pumps power can be corrected according to the difference between the calculated reflected ratios and the real ones. After several iterations, distribution of all the signal power and pump power may converge to an acceptable range, for example, of less than 0.1% variation between the adjacent iterations. After we get the distribution of the pump power and signal power, the noise can be founded by the relaxation method. We assume that the initial noise of each channel is −70 dBm in a channel spacing of 0.2 nm, which is corresponding to the sensitivity limitation of an optical spectrum analyzer (OSA), and the backward noise along

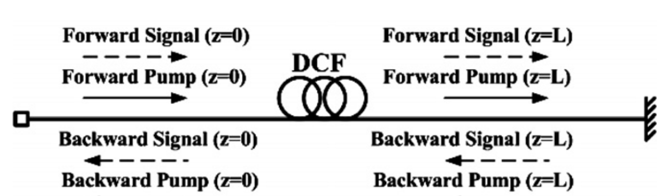

Fig. 2. A simplified equivalent design to present the signal/pump double-pass RFA for simulation purpose.