Optik 125 (2014) 2352–2355

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

An effective numerical method for gain profile optimizations of multi pumped fiber Raman amplifiers

Kulwinder Singh*, Manjeet Singh Patterh, Manjit Singh Bhamrah

University College of Engineering, Punjabi University, Patiala, Punjab, India

ARTICLE INFO

Article history:
Received 20 May 2013
Accepted 14 October 2013

Keywords:
Muti pump Fiber Raman amplifier
Raman gain coefficient
Pump power evolutions
Average net gain
Gain ripple

ABSTRACT

In this paper, we have solved propagation equations of multi-pump fiber Raman amplifier using Runge–Kutta (RK 4th order) numerical method and pump power evolutions along with the fiber length. They are used to calculate the net gain and gain ripple by varying the input signals powers for different fiber lengths. The pump powers are optimized by genetic algorithm and resulting net gain and gain ripple are reported graphically as well as in tabular form. The optimum minimum gain ripple is 0.26 dB for 1 mW input signal powers for 50 km fiber length. By increasing the fiber length gain ripple increases to 0.5 dB for 0.1 mW input signal power. In comparison to other methods reported in the literature, our method is simple to implement and efficient for numerical design of Raman amplification in optical communication systems.

1. Introduction

Modern long haul lightwave system requires broad bandwidth optical amplifiers which can be provided by fiber Raman amplifiers (FRAs) or Raman/EDFA hybrid amplifiers. The gain spectrum of multi pumped FRAs is needed to be adjusted for its use in practical systems. Stimulated Raman scattering (SRS) is a fiber nonlinearity exploited to make fiber Raman amplifiers. A strong optical pump wave amplifies stoke shifted weak optical signal by SRS effect in an optical fiber. A broad bandwidth FRA often requires multiple pumps to generate composite gain spectrum. Generally multi pumped FRAs are designed through rigorous analysis of pump powers and wavelengths adjustments for optimum gain spectrum but strong Raman interactions of pump to pump, signal to signal, and pump to signal make the design somewhat difficult [1,7–11]. Moreover, it is a challenge for researchers to design multi pumped FRA for required gain and gain flatness with certain design constraints such as double Rayleigh backscattering noise and fiber nonlinear effects etc. The coupled differential equations of backward pumped FRAs are generally boundary value problems (BVPs), and are difficult to solve than initial value problems (IVPs) involving forwarding pumping [3]. It has been reported in [4] that forward pumping to FRAs improves the noise figure when used with backward propagating pump than purely backward pumping scheme.

In this paper, we have proposed a numerical algorithm to solve forward pumped Raman amplifier differential equations for signal and pump power evolutions along optical fiber length using Runge–Kutta (4th order) method and a simple genetic algorithm to adjust the average gain and gain flatness by using pump path power integration or effective area of pump power evolution along the fiber. Our work is based on the work reported in Ref. [2]. They had used Newton–Raphson method for gain spectrum adjustment by varying effective pump power combinations. We have used heuristic search method based on GA to optimize the pump power evolutions along the fiber. The optimized pumps are used to calculate the net gain and gain ripple by changing the input signals power for different fiber lengths. In comparison to Refs. [1,3,4] our proposed algorithm is easy to calculate the pump power evolutions, average gain and gain ripple, and effective gain profile optimization.

The paper is organised so that Section 2, presents a theoretical model of multi-pump fiber Raman amplifier differential equations considering signal to signal, pump to signal, and pump to pump interactions. The solution of these differential equations is found by RK (4th order) numerical method and further average net gain and gain ripple is statistically calculated. In Section 3, pump power evolutions are optimized using genetic algorithm and results are plotted and discussed under different conditions. Finally, conclusions have been drawn in Section 4.

2. Theoretical model and numerical algorithm

The major consideration for designing the FRA bandwidth are interactions of pump to pump, signal to signal, pump to signal, as

* Corresponding author. Phone and Fax: +911753046338.
E-mail addresses: ksmalhi@rediffmail.com (K. Singh), mspattar@yahoo.com (M.S. Patterh), manjitsingh_manjit@rediffmail.com (M.S. Bhamrah).

0030-4026/$ – see front matter
http://dx.doi.org/10.1016/j.ijleo.2013.10.069

well as the attenuation. In the steady state the FRA a set of coupled equations can be described as given below [6]

$$\frac{\pm dP(\nu)}{dz} = f(z, \nu_i) = P \pm (z, \nu_i)F(z, \nu_i) \tag{1}$$

(i = 1, 2 . . . . .m)

$$F(z, \nu_i) = -\alpha(\nu_i) + \sum_{j=1}^{i-1} \frac{g_R(\nu_j - \nu_i)}{\Gamma A_{eff}} - \sum_{j=i+1}^{m} \frac{\nu_i}{\nu_j} \times \frac{g_R(\nu_i - \nu_j)}{\Gamma A_{eff}} \tag{2}$$

where, P_i, ν_i, and α_i are the power, frequency, and attenuation coefficient for the ith wave respectively. A_{eff} is the effective area of optical fiber, factor Γ accounts for polarization randomization effects, the value of which lies between 1 and 2, $g_R(\nu_j, \nu_i)$ the Raman gain coefficient from wave j to i. The frequency ratio $\nu_{i/}$ ν_j describe vibrational losses. The plus and minus sign on the left hand side describes the backward and forward propagation waves respectively. The frequency ν_i are numerated in the decreasing order of frequency (i = 1, 2, ...m). The terms from j = 1 to j = i−1 and from j = i+1 to j = m cause amplification and attenuation of the channel at frequency ν_i respectively. The signal evolution along with the fiber can be expressed by the following nonlinearly coupled equation.

$$\frac{dP(z, \nu_i)}{dZ} = -\alpha(\nu)P(z, \nu_i) + P(z, \nu_i)\sum_{j=1}^{N} g_R(\nu_j, \nu_i), P(z, \nu_j) \tag{3}$$

Integrating the Eq. (3) from z = 0 to z = L we can obtain

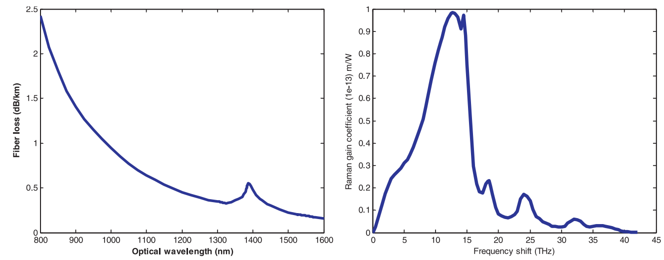
$$\frac{P(L, \nu_i)}{P(0, \nu_i)} = \exp[-\alpha_i L + \sum_{(j=1)}^{N} (g_R)(\nu_j, \nu_i) \int_0^L P(z, \nu_j)dZ] \tag{4}$$

where, L is the length of the fiber. Small signal Raman gain from of the signal ν_i from Eq. (4) can be written as

$$G_i = 10 \times \log_{10} \frac{P(L, \nu_i)}{P(0, \nu_i)} = \exp[-\alpha_i L + \sum_{(j=1)}^{N} (g_R)(\nu_j, \nu_i) \int_0^L P(z, \nu_j)dZ] \tag{5}$$

For a Raman amplifier with N pumps and S signals the net gain of the signals can be expressed in a matrix form as follows:

$$G_{net} \cong 4.343(A + g \times H) = 4.343A + G_{gross} \tag{6}$$



(a) (b)

Fig. 1. (a) Optical wavelength (nm) vs. fiber loss (dB/km), (b) Frequency shift (THz) vs. Raman gain coefficient (m/W) for standard single mode fiber.

where, $G_{net} = [G_1, G_2, \ldots, G_S]$ is the net gain of the signals, $A = [\alpha_1, \alpha_2, \ldots, \alpha_s]L$ is the fiber attenuation of the signals. G_{gross} = 4.343 $g \times H$ is the gross gain of the signals,

$$g = \begin{bmatrix} g_{11} & g_{12} & g_{1N} \\ g_{21} & g_{22} & g_{2N} \\ & & \vdots \\ g_{S1} & g_{S2} & g_{SN} \end{bmatrix} \tag{7}$$

is the Raman gain coefficient between the pumps and the signals where g_{ij} is the Raman gain coefficient between the ith signal and jth pump, and

$$H = [H_1, H_2, \ldots, H_N] \tag{8}$$

where

$$H_j = \int_0^L (P(z, \nu_p)dZ \tag{9}$$

Clearly H_j represents the area under the pump power evolution curve of the jth pump and we denote as effective pump area of the pump. For a given amplifier with given number of pumps and signals, A and g are constant matrices. For the gain profile adjustment pump power in Eq. (6) is varied to get optimum average gain and gain flatness by using genetic algorithm (GA). The main parts of GA include initialization, clustering, sharing, selection, crossover, mutation, and elitist replacement.

3. Results and discussion

Our proposed shooting algorithm employs Runge – Kutta (4th order) numerical method using fixed step size to solve the Raman amplifier differential Eqs. (1) and (2). It calculates the pump power distribution along fiber length. In the calculations following parameters are fixed: there are 36 signal channels launched having wavelength from 1543 (194.43 THz) to 1598 nm (187.73 THz) with input signal power varied 0.1, 0.5, and 1 mW per channel. Standard single mode fiber (SMF) is used with different lengths 50, 60, 70, and

Table 1
Output pump powers for different fiber lengths under different signal launched powers.

Pump wave			Output pump power (mW)								
			Fiber length L = 50 km			L = 60 km			L = 80 km		
No.	Wave length (nm)	Input power (mW)	Signal input power (mW)			Signal input power (mW)			Signal input power (mW)		
			(0.1)	(0.5)	(1)	(0.1)	(0.5)	(1)	(0.1)	(0.5)	(1)
1	1434	45.0	44.9	44.6	44.0	44.9	44.5	43.8	44.9	44.3	43.4
2	1444	45.0	44.0	42.5	39.9	44.4	42.1	38.9	44.2	41.1	36.9
3	1454	50.0	49.6	47.8	45.3	49.5	47.3	44.3	49.3	46.3	42.4
4	1483	100.0	99.7	98.6	96.7	99.7	98.3	96.1	99.6	97.7	94.7
5	1498	100.0	99.8	96.9	96.9	99.7	98.4	96.3	99.6	97.8	95.1