Optimization of Soliton Power and Raman Pump power for Solitons Transmission Systems with Distributed Raman Amplification

F. Yazdani
Núcleo de Engenharia Elétrica- Universidade Federal de Sergipe, UFS, Aracaju-SE, Cep 49100000

L. P. Salles
OptMA[lab] – CPDEE – Universidade Federal de Minas Gerais, UFMG, Belo Horizonte–MG, 31270-010

and J. F. Martins-Filho
Grupo de Fotônica, DES, Universidade Federal de Pernambuco, UFPE, Recife-PE, 50740—530

Abstract **¾ We present novel analytical and numerical techniques for the estimation of input soliton power and Raman pump power in counter-propagating and bidirectional amplification schemes. The obtained values by the iterative 4th-order Runge-Kutta method are verified by split step propagation simulation along the fiber. Although the results are validated at small dispersion of fiber, the propagation simulations by split step show the gradual elevation of signal power preemphasis as a function of fiber dispersion. The optimized results are confirmed by a simulated 40 Gb/s soliton transmission system with distributed amplification.**

Keywords **¾ Optical amplifiers, Fiber optics communications, Soliton, Raman amplification, 4th-order Runge-Kutta, Split step, Nonlinear Schrödinger equation.**

I. INTRODUCTION

Distributed Raman amplifier has emerged as the most attractive amplifier for high speed optical communication systems. It can be used for loss management in high-capacity, long-haul transmission based on optical solitons [1]. It is the best method to compensate the fiber loss, minimizing the peak power destruction of optical pulses. For this reason the noise immunity is higher than in other schemes. The low noise performance of Raman amplifiers leads to reduction of required average power of optical channel to achieve the acceptable signal to noise ratio. This reduction in signal power leads to the reduction in nonlinear impairments improving the overall system performance. Also, it overcomes the limit of amplifier spacing (L_a) imposed by lumped amplification to be a fraction of the dispersion length (L_D) [2]. This characteristic is crucial in ultra high bit rate per channel systems, where the dispersion length can become quite small [1].

The loss management of soliton pulses is optimized for an elevated power of solitons respect to the lossless system, by a factor called the enhancement factor (N^2). Exactness of signal power enhancement is important because an overestimated correction of signal power leads to excessive generation of dispersive waves and additional nonlinear phase changes. The phase change originates from amplitude modulation of the pulse train during propagation, which results in pulse shape distortion. In addition, the dispersive waves become background noise. On the other hand, the pulsewidth increases along the propagation in the fiber for under estimated values of N^2, rising the intrapulse interaction that leads to the decrease of the reach of the system [1]. Also, the pump power in Raman loss management is important, such that over estimation leads to adiabatic evolution of fundamental soliton and pulse compression. In the other extreme, the under estimation of pump widens the pulsewidth along the propagation.

Although there are well analyzed soliton transmission in lossy fibers in the literature [3,4], the lack of analytical expression for solitons power enhancement is felt. In this paper, we present a technique for predicting Raman pump power and input peak power of solitons to manage the fiber loss, using analytical and numerical methods. We present a formulation for the signal power (P_s) and pump power estimation ($P_p(l_p)$) for a single channel solitons in section II and III. The result was verified using simulations of soliton propagation by split-step method [5] and also using a commercial simulator of optical communication link in section IV. Finally, the conclusion is presented in section V.

II. ANALYTICAL ESTIMATION METHOD

The evolution of a train of optical soliton pulses along a distributed amplified optical fiber is obtained by numerical solution of the nonlinear Schrödinger (NLS) equation, including the effective attenuation coefficient [1,2]:

$$\begin{aligned} & i\partial A/\partial z - b_2/2\partial^2 A/\partial t^2 + g\cdot|A|^2\ A = -i a_{eff}(z)/2A, \\ & a_{eff}(z) = -\,dP_s(z)/dz/P_s(z), \end{aligned} \tag{1}$$

where A, b_2, γ,?P_s, are the slowly varying pulse amplitude, group velocity dispersion, nonlinear parameter of the fiber, and the power variation of optical soliton, respectively. Here, a_{eff} is the effective attenuation that is a periodic function of z with period L_a. Using the transformation:

$$\begin{aligned} & A = \exp(\,-\int_0^z a_{eff}\ (z)/2\,dz\,)\cdot u(z,t) \\ & f(z) \equiv \exp(\,-\int_0^z a_{eff}\ (z)/2\,dz\,), \end{aligned} \tag{2}$$

Farshad@ufs.br. Tel +55-79-2105-6834, Fax +55-79-2105-6807; luciana@cdpee.ufmg.br, Tel. +55-31 3409-3497. jfmf@ufpe.br, Tel. +55-81-21268210, This work was financed partially by CNPQ and CAPES, project no. 151272/2004-2, 350300/2004-6.

and considering rapid variations of *f(z)* in comparison to *u(z,t)* along the amplification span, the effect of *f(z)* in NLS equation is averaged out. Accordingly, the NLS equation is converted to:

$$i\partial u/\partial z - b_2/2\partial^2 u/\partial t^2 + g\cdot\exp(-\int_0^z a_{eff}(z)dz)\,|u|^2\,u = 0. \tag{3}$$

One can replace *f(z)* by its average over one amplification period, equivalent to transmission of path-averaged-solitons [1]. Therefore, the NLS equation can be solved numerically for the fundamental solitons at the fiber input with power enhancement given by:

$$N^2 = \frac{L_a}{\int_0^{L_a}\exp(-\int_0^z a_{eff}(x)dx)dz}. \tag{4}$$

The time averaged evolution of signal power $P_s(z)$ is influenced by the Raman gain. In the bidirectional cw pumping scheme the optical power evolution is given by the following simplified equations, for parallel polarization of signal and pump [1,3]:

$$\begin{aligned}
&dP_s/dz = g_R(\Delta n)(P_{pb}+P_{pf})\cdot P_s - a_s P_s \quad P_s(0) = P_s B T_0\\
&dP_{pb}/dz = n_p/n_s\, g_R(\Delta n)\cdot P_{pb}\cdot P_s + a_p P_{pb} \quad P_{pb}(La) = P_{pb}\\
&dP_{pf}/dz = -n_p/n_s\, g_R(\Delta n)\cdot P_{pf}\cdot P_s - a_p P_{pf} \quad P_{pf}(0) = P_{pf},
\end{aligned} \tag{5}$$

where $P_s(z)$, $P_{pf}(z)$, $P_{pb}(z)$, a_s, a_p, T_0, B, $g_R(Dn)$ account for time averaged evolution of signal and pump powers (forward and backward), fiber loss (km^{-1}) at signal (n_s) and pump (n_p) frequencies, pulsewidth, bit rate, and Raman gain ($W^{-1}\,km^{-1}$) at $Dn=n_p-n_s$, respectively. An analytical solution is available for this set of equations, considering no depletion of counter-propagating pump. It occurs when the signal power remains much smaller than the pump power, known as small signal operation. Hence**,** for equal pump power in both directions, the power enhancement of soliton and the required pump powers can be approximated by:

$$N^2 = L_a \Bigg/ \left\{ \int_0^{La} \exp\left[-a_s z + \frac{e^{-a_p La}(\exp(a_p z)-1)}{a_p} g_R(\Delta n) P_{pb} + \frac{(1-\exp(-a_p z))}{a_p} g_R(\Delta n) P_{pf} \right] dz \right\}.$$

$$P_{pf} = P_{pb} = \frac{a_p\cdot\ln(G_{On\_Off})}{2(\exp(a_p L_a)-1)\cdot g_R(\Delta n)}; \quad G_{On\_Off} = \frac{P_s(L_a)}{P_s e^{-a_s La}} \tag{6}$$

III. Numerical Estimation Method

The analytical solution of bi-directional Raman amplification is acceptable in small signal approximation, where depletion of counter propagating pump is negligible. Otherwise, more accurate results should be obtained by numerical method. In this case, the iterative method of calculation is executed, applying the analytical solutions as the seed. The set of differential equations described in (5) is resolved as initial value problem, considering the boundary values at the fiber input (*z=0*) as: $P_{pb}(0)= P_{pb}\exp(-\alpha_p L_a)$, $P_{pf}(0)= P_{pf}$ and $P_s= P_0 N^2$, where $P_0= |b_2|/(T_0^2\gamma)$, is the fundamental solitons power in lossless fiber.

The coupled differential equations described in (5) are solved using 4th-order Runge-Kutta method (RK). Based on the solution, the pump power $P_{pb}(z)$ at output side of the fiber ($z=L_a$) is obtained. If this value is larger than P_{pb}, the initial power of counter-propagating pump at input side is reduced a little and vice versa. Then, the power of soliton is preemphasized using new value of enhancement factor (Equation 6). The above procedure is repeated iteratively until $P_{pb}(L_a)-P_{pb}$ converges to zero with acceptable error margin. Then, the on-off gain of Raman amplification G_{on-off} is obtained as described by (6). For insufficient gain, the power of counter-propagating pump is raised a little and the above procedure is repeated iteratively. In this manner, the power enhancement factor and the required pump powers are estimated. In the next step, the evolution of solitons is obtained by numerical solution of NLS equation, applying the effective attenuation (α_{eff}(z)) along the optical fiber.

IV. Numerical Results

Fig (1) shows the results of numerical calculation of power enhancement as a function of b_2, for soliton pulse $A(0,t)=\sqrt{P_s}Sech(t/T_0)$ with T_0= 4.2 ps, L_a= 50 km, γ=2.108 $km^{-1}W^{-1}$, $g_R(Dn)$= 0.645 $km^{-1}W^{-1}$, A_{eff}= 50 μm^2, a_p= 0.247 dB/km, and a_s= 0.203 dB/km are for the pump wavelength of 1.452 μm and signal wavelength near to 1.55 μm. The results of iterative RK method show the signal power does not required to be preemphasized in bidirectional pumping scheme of Raman amplifier (N^2= 1) and is independent of GVD dispersion value. However, it is necessary to enhance the soliton power up to 60% (N^2= 1.6) in counter pumping scheme of Raman amplifier. The analytical solution for soliton power in lumped amplification scheme shows the requirement to 160% power enhancement of fundamental single soliton in average-soliton regime (N^2= 2.6) [5]. Higher power of input soliton in lumped method should increase the destructive effects of fiber nonlinearities on soliton propagation, decreasing the transmission reach. The iterative RK method is also used to find the power of counter propagating pump (P_{pb}) for a given fiber dispersion. The variation of normalized pump power (N_p) with respect to its analytical value as described by equation (6) is illustrated in Fig. 1, for two scheme of Raman amplification. As can be seen, the pump depletion is negligible for small values of b_2, but it increases linearly about 20% in bidirectional pumping scheme for the given dispersion range. The rate of pump depletion grow in function of b_2, is reduced to 10% in counter- pumping configuration.

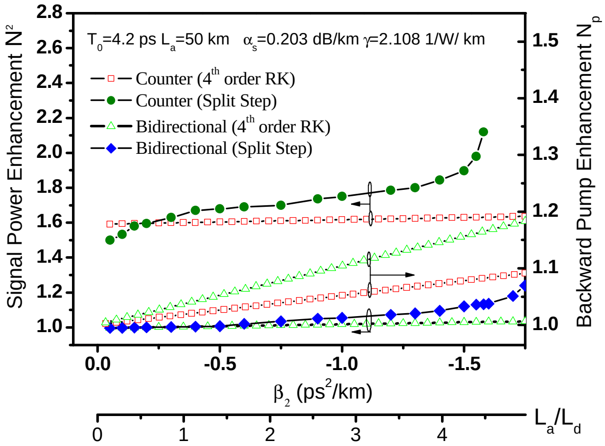

Fig. 1. Power enhancement of soliton and pump as a function of fiber dispersion for loss managed by Raman amplification (bidirectional and counter propagating pump). The results were obtained for a single soliton pulse evolution through one span of amplification (L_a) by iterative RK method and simulation of soliton propagation to keep constant the pulsewidth.

The above result is verified by the propagation simulation of a single soliton over one span of Raman amplification (L_a). For this purpose, the nonlinear Schrödinger equation is solved numerically for the fundamental soliton using Split-step Fourier method while the effective attenuation coefficient is included in NLS equation. The pulsewidth is considered large enough to get ride of effects of higher order dispersion, self phase modulation, self phase steepening, and delayed Raman response, to simplify the simulation of single soliton propagation. The power of input soliton is varied and the simulation is repeated for a given GVD dispersion to find an optimum value to maintain a fixed pulsewidth (DT_0=0). The required power enhancement N^2 for a given fiber dispersion is illustrated in Fig. 1, considering two schemes of amplification. As expected, the results of propagation simulation and of iterative RK method are in the same order of magnitude, especially for small fiber dispersion. Also, for the bidirectional pumping scheme there is a good agreement between numerical calculations by iterative RK method (N^2_{RK}) and simulation results of soliton transmission. The simulation results show the gradual increase of required soliton power in function of b_2, indicating the more nonlinearity effects at larger dispersion. In addition, it is impossible to maintain fixed the pulsewidth for GVD dispersion larger than 1.75 ps^2/km in bidirectional pumping scheme. This value is reduced to 1.58 ps^2/km in counter pumping scheme of Raman amplification. As expected, more steady power of pulses along the propagation leads to more immunity of solitons to fiber dispersion, as occurs in bidirectional pumping scheme.

The pulsewidth variation as a function of N^2 is obtained by simulation of soliton propagation through one span of amplification (L_a), considering the fiber dispersion as a parameter. In bidirectional-pumping (Fig.2-a) the pulsewidth is maintained fixed for dispersion as small as 0.05 ps^2/km, such that pulse widening does not occur at almost all values of signal power. For dispersion values higher than 0.5 ps^2/km and lower than 1 ps^2/km, the required soliton power is the same as estimated analytically, while for 1.0 ps^2/km <$|b_2|$<1.7 ps^2/km the power enhancement rises 20% to keep the constant pulsewidth. The simulation of soliton propagation in dispersive fiber with higher dispersion than 1.7 ps^2/km leads to inevitable increase in the pulsewidth.

Moreover, in counter-pumping scheme (Fig.2-b) the pulsewidth is maintained fixed for dispersion values as small as 0.025 ps^2/km, such that pulse widening does not occur at almost all values of signal power. For $|b_2|$< 0.5 ps^2/km the required value of N^2 is lower than the numerically estimated value (N^2~1.6), while for 1 ps^2/km <$|b_2|$< 1.58 ps^2/km the power enhancement rises 20% more than the analytical results to keep the constant pulsewidth. Fig. 2-b shows that adiabatic compression does not occur for larger values of $|b_2|$.

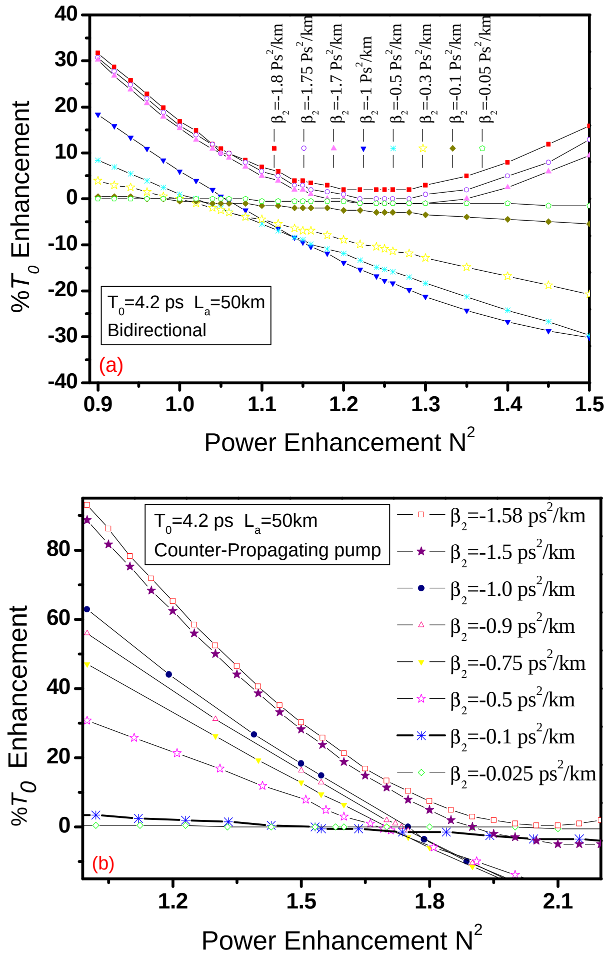

Fig. 2. Simulated pulsewidth variation as a function of power enhancement after one span of single soliton pulse transmission, in distributed Raman amplification, using a) Bidirectional pump. b) Counter-propagating pump.

At the next step, the results of numerical simulation are applied to a commercial software (LinkSim) to simulate a 128-bit PRBS soliton transmission at a bit rate of 40 Gb/s. The Raman simulator provides additional effects of Rayleigh scattering, spontaneous Raman emission, its temperature dependence, intrapulse Raman scattering, stimulated Raman scattering, and high order Stocks generation that are of interest for the simulation of short pulse propagation [4]. In addition, the polarization effect of the pump is considered.

The Raman gain is determined using an experimental curve of Raman effect of a SMF silica fiber. The transmission system is modeled through the solution of the four coupled equations related to the spectral densities of four variables as forward and backward signals, pump, and noise. The Rayleigh scattered power is regarded as noise.

The simulation results for the two schemes of loss management, as counter propagating pump and bidirectional pumping is shown in Fig. 3. The 4 ps soliton pulse train at 40 Gb/s is applied to a fiber with counter propagating pump and amplification length of 50 km, the transmission length (L_T) is 1000 km and the fiber dispersion for the selected channel is about -0.25 ps^2/km. As it can be seen, the maximum Q is obtained at the numerically estimated value (N^2~ 1.6) obtained by RK method. In the other simulation, 2.5 ps soliton pulses with rate of 40 Gb/s is applied to a 50 km loss compensated fiber by bidirectional pumping scheme, the transmission length is 1300 km and the fiber dispersion for the selected channel is about -0.3 ps^2/km. The results confirm the same optimum value of N^2 as obtained by RK method.

In the other hand, simulation results of the soliton propagation shows the higher power requirement at larger dispersion parameter. The excess power helps to keep fixed the pulsewidth by adiabatic pulse compression but induces the distortion of hypersecant pulse shape. In this way, the pulse is restricted to the bit slot (*1/B*) that improves the bit error rate, but the soliton distortion deteriorates seriously the reach of the system. To clarify this, the soliton transmission of Fig. 3 is simulated again at 40 Gb/s in a dispersive fiber with -0.5 ps^2/km, using counter propagating pump Raman amplification. Results shows that the reach drops to 500 km with a Q factor as low as 8, increasing the preemphasis factor up to 2.5 that is much higher than the estimated value shown in Fig. 3.

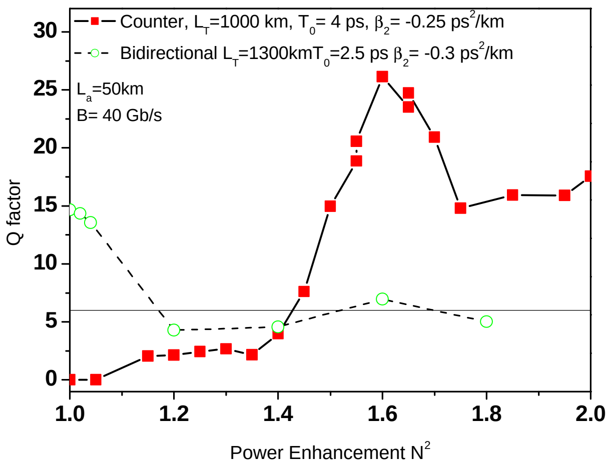

Fig. 3. Q factor of a 40 Gb/s soliton transmission system with counter and bidirectional pumping of distributed Raman amplification.

V. Conclusions

We presented analytical and numerical methods for estimation of soliton power enhancement and corresponding pump power for two schemes of distributed Raman amplifier, using 4th-order Runge -Kutta method. The obtained values by the 4th-order Runge -Kutta method were verified through split step simulation of soliton propagation along the one amplifier length to maintain fixed the pulsewidth. Although the results were matched at small dispersion of fiber (L_a/L_D<1), the simulations showed the gradual elevation of power emphasis as a function of GVD dispersion. Also the results were validated through the simulation of a 40 Gb/s soliton transmission system with counter and bidirectional pumping schemes at small value of second order fiber dispersion. For this purpose, a commercial simulator of optical link was utilized.

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