Effects of ASE Noise and Dispersion Chromatic on Performance of DWDM Networks using Distributed Raman Amplifiers

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***Abstract*:** We investigate effects of amplified spontaneous emission noise (ASE), noise figure (NF) and dispersion chromatic on the performance of DWDM networks using distributed optical fiber Raman amplifiers (DRAs) in two different pump configurations, i.e., forward and backward pumping. We found that the pumping configurations, ASE noise, and dispersion play an important role in network performance improving since it reduces noise figure and bit error rate (BER) of the system. Simulation results show that the lowest bit error rate and noise figure when using forward pumping configuration. Moreover, we have also compared ASE noise powers of the simulation with these of the experiment, they are match.

***Keywords*:** Dense Wavelength Division Multiplexing (DWDM), DRA (Distributed Raman Amplifier), amplified spontaneous emission (ASE).

1. Introduction

Nonlinear effects within optical fiber such as stimulated Raman scattering, stimulated Brillouin scattering or stimulated four-photon mixing may also be employed to provide optical amplification by injecting a high-power laser beam into optical fiber. Among these Raman, amplification exhibits advantages of self-phase matching between the pump and signal together with a broad gain-bandwidth in comparison with the other nonlinear processes. Thus it is attractive for current dense wavelength division multiplexed (DWDM) systems since it provides gain over the entire fiber band [1].

One of the most usable in the contemporary submarine and long-haul terrestrial networks is the distributed Raman amplifiers (DRAs) used stimulated Raman scattering (SRS) effect, which has many advantages: stimulated Raman amplification can occur in any fiber at any signal wavelength by proper choice of the pump wavelength; the Raman gain process is very fast and the effective noise figure (NF) of DRA is smaller than the one of Erbium-doped fiber amplifier (EDFA) and/or the semiconductor optical amplifier [2,3].

In a DWDM system to reach a long transmission distance and have flat gain-bandwidth, we used a DRA amplifier. However, such an optical amplifier also generates amplified spontaneous emission (ASE) noise [4], which will limit system performance to an electrical signal to noise ratio at the photodiode determined by the spontaneous-spontaneous and carrier-spontaneous beat noise. Several transmission experiments using distributed Raman amplification technology have been reported, but so far, there are very few theoretical nor experimental reports on the noise performance comparison between the pumping configurations of the low-power pumped Raman amplification system for the middle-distance networks. Thus, based on proposed architecture, we analyze the effects of ASE noise on the performance of DWDM networks.

In this paper, we use theoretical and simulation model of distributed Raman optical amplifier in SMF-28 bidirectional optical fiber with two different pumping configurations at pump wavelength of 1470 nm and pump power of 880mW, which is smaller than traditional Raman amplifier's pump. We calculated ASE noise powers and its affection to bit error rate and noise figure of the system. Moreover, we also compare these noise powers with experimental results of the real WDM network system.

The rest of this paper is organized as follows. In Section II, we present the theoretical analysis of different pump schemes. In Section III, we show the simulation setup of a DWDM system, the simulation and experiment results, and discussion. Finally, Section IV concludes the paper.

2. Theoretical Analysis

In this section, we analyze distributed Raman amplification in DWDM transmission systems using both forward and backward pumping. Consider the simplest situation in which a single continuous wave (CW) pump beam is launched into a single-mode fiber with distance L of a transmission system to amplify several CW signals. The evolution of the input signal power of *i*th channel in DWDM system P_{si} and the input pump power P_p propagating along the single-mode optical fiber in milliwatt, can be expressed by the following different equations called propagation equations that include pump-to-pump, signal-to-signal and pump-to-signal Raman interactions, spontaneous Raman emission and its temperature dependency, stimulated Raman scattering, pump depletions due to Raman energy transfer, high-order stokes generation, multiple Rayleigh backscattering, fiber loss and spontaneous emission noise can be expressed by the following equations (1, 2, 3) [5-9]. Noise propagates in both directions with powers P_n^+ and P_n^-.

Where g_R is the Raman gain efficiency in $W^{-1}km^{-1}$ of the fiber normalized with respect to the effective area $A_{eff} = \pi r^2$ of the fiber, α_p, α_{si} and α_n are the attenuation coefficients in km^{-1} at the pump, the *i*th WDM component of the signal and noise frequencies (f_p, f_{si}, and f_n), γ is the the Rayleigh backscattering coefficient in km^{-1}. The upper signs of $\pm$ and $\mp$ in three equations correspond to the forward propagating pump and the lower signs correspond to the backward propagating pump. K is the polarization factor ($g_R = g_r / KA_{eff}$), Δf is the frequency interval, h is Plank's constant, k_B is the Boltzmann's constant and T is the absolute temperature.

$$\frac{dP_p^{\pm}}{dz} = \mp\alpha_p P_p^{\pm} \pm \gamma P_p^{\mp} \mp \sum_{i=1}^{N} \frac{f_p}{f_{si}} g_R P_p^{\pm} P_{si}^{+} \mp \left(\sum_{i=1}^{N} g_R P_p^{\pm} h f_{si} \Delta f \right) \left[1 + \frac{1}{e^{h(f_p - f_{si})/k_B T} - 1} \right] \tag{1}$$

$$\frac{dP_{si}^{+}}{dz} = -\alpha_{si} P_{si}^{+} + \gamma P_{si}^{-} + g_R P_p^{\pm} P_{si}^{+} + 2h f_{si} \Delta f g_R P_p^{\pm} \left[1 + \frac{1}{e^{h(f_p - f_{si})/k_B T} - 1} \right] \tag{2}$$

$$\frac{dP_n^{\pm}}{dz} = \mp\alpha_n P_n^{\pm} \pm \gamma P_n^{\mp} \pm g_R P_p^{\pm} P_n^{\pm} \pm g_R P_p^{\pm} h f_n \Delta f \left[1 + \frac{1}{e^{h(f_p - f_n)/k_B T} - 1} \right] \tag{3}$$

Two first terms in these equations are fiber loss and Rayleigh backscattering, two last terms in Eq. (1) refer to the signal and the ASE noise induced pump depletion. The third and fourth terms in Eq. (2) include stimulated and spontaneous Raman amplification. The last term in Eq. (3) refers to the spontaneous emission noise power generated at the frequency f_n over a bandwidth Δf.

It is possible to derive an explicit analytical solution using a simple iteration method [5] in two following pumping configurations.

2.1 Forward Pumping

In forward pumping case, signal and pump waves are propagated from z=0 to z=L in +z direction. The differential equations are solved by analytical method without pump depletion at point z as in [8].

$$P_p^{+}(z) = P_p(0)\exp(-\alpha_p z) \tag{4}$$

$$P_{si}(z) = P_{si}(0)\exp\left[-\alpha_{si} z + g_R P_p(0) \frac{1 - \exp(-\alpha_p z)}{\alpha_p} \right] \tag{5}$$

$$\begin{aligned} P_n^{+}(z) = [& h f_n \Delta f \exp(-q_n^{+})(q_n^{+})^{\alpha_n/\alpha_p} \\ & \times(\Gamma_1(1+\frac{\alpha_n}{\alpha_p}, q_n^{+}) - \Gamma_1(1+\frac{\alpha_n}{\alpha_p}, q_n^{+}\exp(-\alpha_s z))) \\ & \times\exp(-\alpha_n z + q_n^{+}(1-\exp(-\alpha_p z))] \end{aligned} \tag{6}$$

$$\begin{aligned} P_n^{-}(z) = [& h f_n \Delta f \exp(q_n^{+})(q_n^{+})^{-\alpha_n/\alpha_p} \\ & \times(\Gamma_2(1+\frac{\alpha_n}{\alpha_p}, q_n^{+}\exp(-\alpha_s z)) - \Gamma_2(1+\frac{\alpha_n}{\alpha_p}, q_n^{+}\exp(-\alpha_s L))) \\ & \times\exp(-\alpha_n z - q_n^{+}(1-\exp(-\alpha_p z))] \end{aligned} \tag{7}$$

Where

$$q_n^{+} = \frac{g_R P_p(0)}{\alpha_p} \tag{8}$$

$$\Gamma_1(\alpha, u) = \int_0^u t^{-\alpha+1}\exp(t)dt \tag{9}$$

$$\Gamma_2(\alpha, u) = \int_0^u t^{\alpha-1}\exp(-t)dt \tag{10}$$

2.2 Backward Pumping

The backward pumping case can be considered in a similar fashion. Here pump wave is propagated from z=L to 0 in –z direction, solutions of Equations (1-3) with pump depletion due to the backward stimulated process is neglected as [8].

$$P_p^{-}(z) = P_p(L)\exp(-\alpha_p(L-z)) \tag{11}$$

$$\begin{aligned} P_{si}(z) = P_{si}(0)\exp[& -\alpha_{si} z + g_R P_p(L) \\ & \times\exp(-\alpha_p L)\frac{\exp(-\alpha_p z) - 1}{\alpha_p}] \end{aligned} \tag{12}$$

$$\begin{aligned} P_n^{+}(z) = [& h f_n \Delta f \exp(q_n^{-})(q_n^{-})^{-\alpha_n/\alpha_p} \\ & \times(\Gamma_2(1+\frac{\alpha_n}{\alpha_p}, q_n^{-}\exp(\alpha_s z)) - \Gamma_2(1+\frac{\alpha_n}{\alpha_p}, q_n^{-})) \\ & \times\exp(-\alpha_n z + q_n^{-}(\exp(\alpha_p z) - 1))] \end{aligned} \tag{13}$$

$$\begin{aligned} P_n^{-}(z) = [& h f_n \Delta f \exp(-q_n^{-})(q_n^{-})^{\alpha_n/\alpha_p} \times(\Gamma_1(1+\frac{\alpha_n}{\alpha_p}, q_n^{-}\exp(\alpha_s L)) \\ & -\Gamma_1(1+\frac{\alpha_n}{\alpha_p}, q_n^{-}\exp(\alpha_s z))) \\ & \times\exp(\alpha_n z - q_n^{-}(\exp(-\alpha_p z) - 1)] \end{aligned} \tag{14}$$

Where

$$q_n^{-} = \frac{g_R P_p(L)\exp(-\alpha_p L)}{\alpha_p} \tag{15}$$

The total variance of the noise current is the sum of all variances of thermal noise, shot noise, beat noise and can be written as

$$\sigma_{total}^2 = \sigma_{th}^2 + \sigma_{shot}^2 + \sigma_{beat}^2 \tag{16}$$

Where σ_{th} is thermal noise, σ_{shot} is the shot noise which is generated by signal, pump and ASE, σ_{beat} is beat noise, it consists of the signal-ASE beat noise, the ASE-ASE beat noise (beating between the spectral components of the added amplifier ASE), the pump-ASE beat noise and the signal-signal beat noise [10].

Finally, the bit error rate (BER) can be calculated as

$$BER = \frac{1}{2} erfc\left(SNR\right) \qquad (17)$$

Where $erfc(.)$ is the complementary error function, and signal- to- noise rate is written as [2]

$$SNR = \frac{I_{signal}(ith)}{\sigma_{total}\sqrt{2}} \qquad (18)$$

$I_{signal}(ith)$ is photocurrent of ith channel at the output of photodiode.

3. Simulation and Experiment Results

3.1 Simulation Setup

In this section, we set up a DWDM network model by using OptiSystem 7 software to compare ASE noise powers with previous experimental results. In this model, we used a distributed Raman amplifier with different two pump schemes are forward and backward pumping. Fig. 1 shows the system with the propagation of 16 DWDM channels located between 193.1 THz and 193.85 THz, 50 GHz spaced to each other, and a pump wavelength of 1470 nm. A PRBS generator generates the downstream traffic of each channel, which generate pseudo random bit sequences. These bit sequences are then used to control NRZ generators to generate non-return-to-zero signals. OOK modulation between a NRZ signal and a continuous wave (CW) laser source is carried out by using a Mach-Zehnder modulator.

Signals are multiplexed at a multiplexer and then they are combined with the pump at a WDM coupler that transmits them into the bi-directional single-mode optical fiber in the same direction, it is called forward pumping scheme. In addition to, has also a pump laser is located at the output of the optical fiber; it is called the counter or backward pumping. The signal then will be amplified by stimulated Raman scattering scheme in single-mode fiber medium.

In the receiver side, the signal is converted into photocurrent by using a PIN photodetector. BER of the received signal is analyzed by using a BER analyzer in combination with a low pass Bessel filter.

3.2 Simulation Results

Simulations have been carried out to estimate the effects of ASE noise, noise figure, and chromatic dispersion on performance of the network in different pump configurations. Key parameters used for this simulation are listed in Table 1.

Table 1. Simulation parameters

Name	Symbol	Value
Length of DRA	L	0 ÷ 90 km
Effective area	A_{eff}	80 μ^2
Bit rate	R_b	10Gbps
Signal frequencies	f_s	193.1 – 193.85 THz
Pump wavelength	λ_p	1470 nm
Pump power	P_p	880mW
Dispersion chromatic	D	14, 15, 16 ps/ nm.km

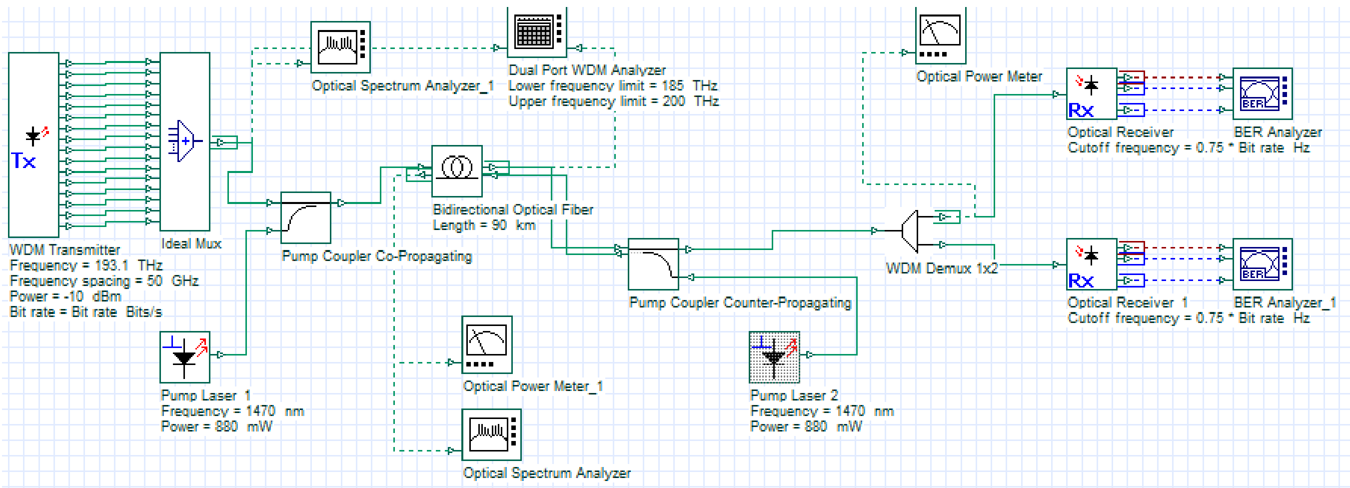

Figure 1. Block diagram of a DWDM system using distributed Raman amplifier

Figure 2 shows how the first channel signal and pump powers vary with the DRA amplifier length for different pumping configurations, i.e., forward and backward pumping. We can see that, as the amplifier length increases, pumping power increases in backward direction. While in the forward pumping it decreases.

In the forward pumping case, there is a larger gain in the signal power. This result, increasing effects of nonlinearities in the fiber length [5]. In the backward pumping, the gain occurs towards the end of the fiber after the substantial power loss. This power loss will increase the possibility of noise altering the quality of the signal.

Figure 3 shows forward and backward noise powers as a function of the amplifier length of the first signal channel (193.1THz) when $P_s = -10 dBm$ and We can see that in the forward pumping case both forward and backward DRA noise powers are smaller than those in backward pumping. Forward pumping is more advantageous than backward pumping from the viewpoint of minimizing noise.

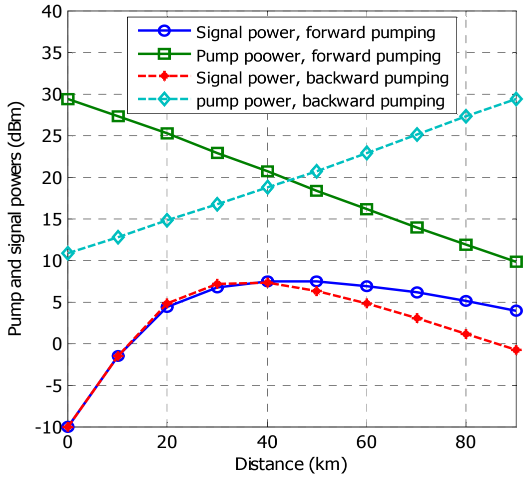

Figure 2. Signal and pump powers as a function of amplifier length (L) with $P_s(0) = -10\ dbm, P_p = 880mW$

Fig. 4 shows the noise figure as a function of the DRA amplifier length for forward and backward pumping. As we can see when amplifier length is short noise figure is the same, on the other hand, for longer fiber length become remarkable because of the accumulation of noise along the fiber is different in the two cases. The noise figure is no change when the length of amplifier increases in forward pumping configuration. However, it has increased quickly in the backward pumping case.

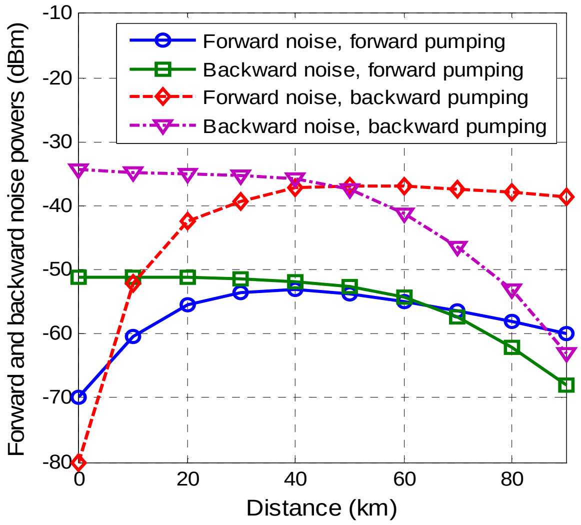

Figure 3. Noise powers as a function of amplifier length (L) with $P_s(0) = -10dbm, P_p = 880mW$

In figure 5, we fix dispersion chromatic coefficient $D = 16\,ps/nm.km$ and the amplifier length of 90 km. We investigate BER versus transmitted power for two cases, with and without ASE noise in forward and backward pumping configurations. It is seen that the effect of ASE increases in backward pumping case. More specially, the power penalty due to ASE noise at BER 10^{-9} is about 2dB when forward pumping. While in backward pumping, it increases to 2.3dB. It is because, according to Eqs. (6, 7, 13, 14) and Fig. 3, ASE noise powers in the backward pumping scheme are greater these in forward pumping case.

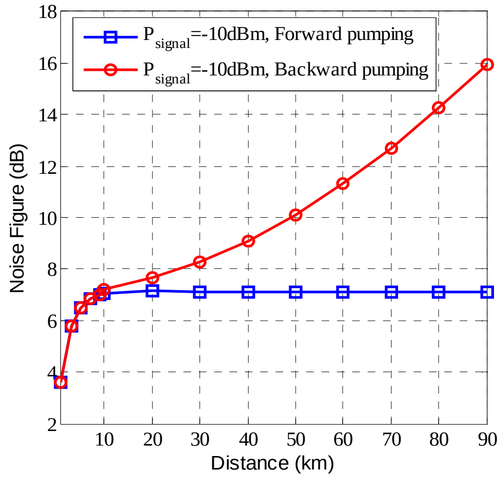

Figure 4. Noise figure as a function of DRA amplifier length (L) with $P_s(0) = -10dbm, P_p = 880mW$

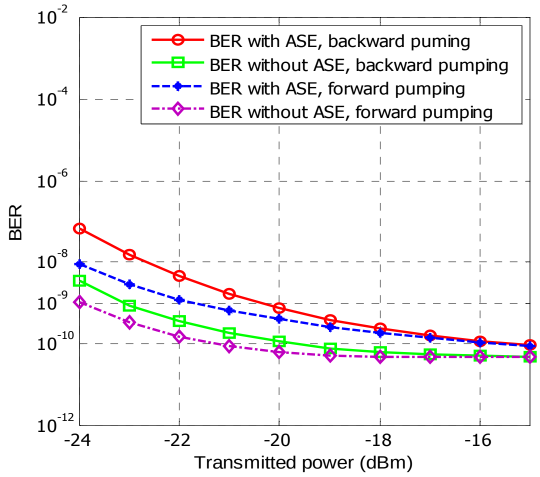

Figure 5. BER vs. transmitted power with R_b=10Gbps, D=16 ps/nm.km, L=90 km

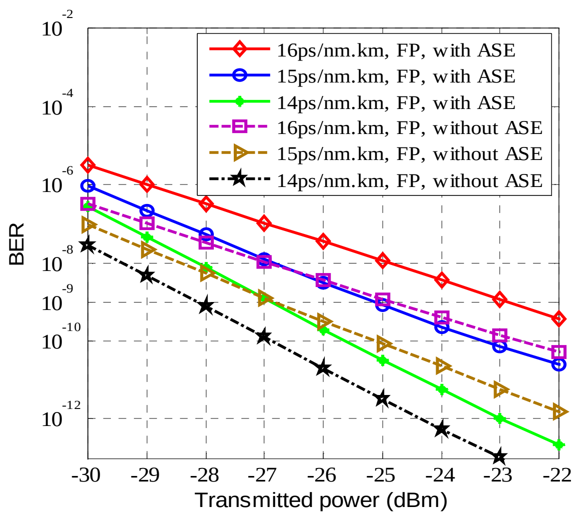

Figure 6. BER vs. transmitted power with D= (14, 15, 16) ps/nm.km, L=90 km, forward pumping (FP)

Figures 6 and 7 show the dependence of BER on the transmitted power for two cases, forward and backward pumping with three different values of dispersion Chromatics D (14, 15 and 16 ps/nm.km). It is seen that, BER increases when D increases. Moreover, in Fig. 6, the forward pumping case, the power penalty at BER 10^{-9} without ASE is about 2 dB (D=16ps/nm.km) while it increases up to 2.3 dB when ASE noise is considered as denoted in Fig. 7.

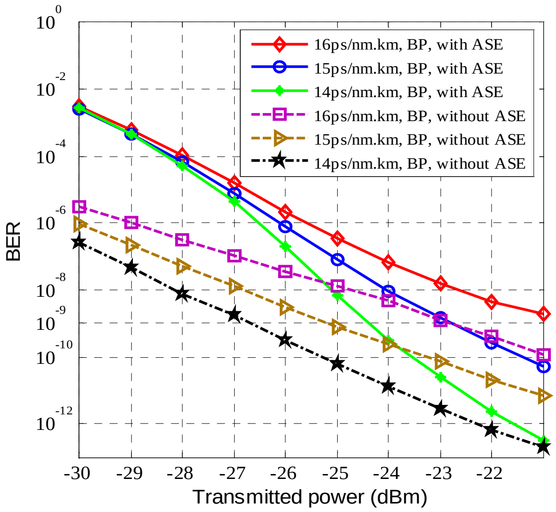

Figure 7. BER vs. transmitted power with D= (14, 15, 16) ps/nm.km, L=90 km, backward pumping (BP)

3.3 Experiment Results

Experiments have been carried out on the real WDM system to investigate spontaneous and stimulated Raman scattering effect in SMF-28 fiber. For no extra-high power pump source is available, three pump lasers at 1470nm with a total power of 880mW, combined through a combiner, are used as a replacement. In this system we used a 1480/1550 WDM coupler to couple total pump power in the forward direction into the fiber where signals pass through it.

Figure 8 shows the emission spectral of signal at a wavelength of 1552.52nm without and with Raman amplification. It is seen that the signal amplified up to 11dB while its bandwidth and wavelength are no change. However, the ASE noise power at the signal wavelength increases about 13dB compare with the case the signal is not amplified. This proves that, ASE noise is considerably in the presence of amplification.

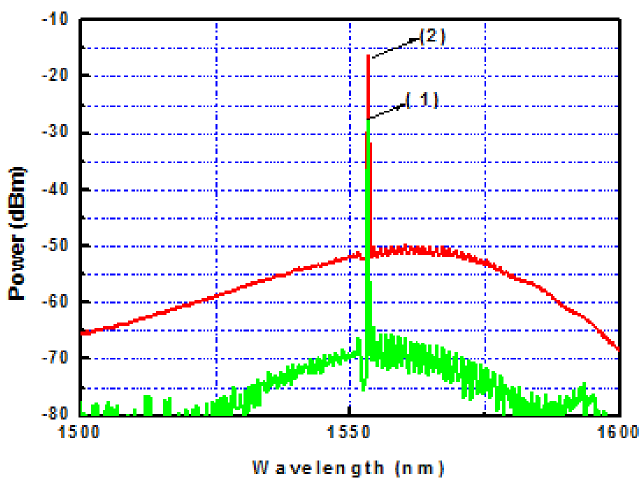

Figure 8. Signal spectral, without (curve 1) and weight gain (curve 2), L=90km and P_p=880mW

4. Conclusion

In this paper, we have analyzed the theory and simulated a DWDM network system using a distributed Raman amplifier pumped in two different directions. Moreover, we analyzed the effects of ASE noise, noise figure, and dispersion chromatic on the performance of DWDM-based system. We found that the different pumping configurations, ASE noise, and dispersion play an important role in network performance improving since it reduces noise figure and bit error rate (BER) of the system. Simulation results show that the lowest bit error rate and noise figure when using forward pumping configuration when the fiber amplifier length of 90 km. These results are also compared with the results of the experiment and they are matched. These results conclude that DRA with low pump power (<1W) is the promising key technology for short– and/or middle-distance DWDM transmission networks.

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