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Influence of ASE Noise on the Performance of DWDM Networks Using Low-Power Pumped Raman Amplifiers

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ABSTRACT
We present the results of investigation of influence of amplified spontaneous emission (ASE) noise, noise figure (NF) and dispersion chromatic on the performance of middle-distance dense-wavelength-division-multiplexing (DWDM) networks using low-power pumped distributed 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 for improving the network performance by reduction of NF and bit error rate (BER) of the system. Simulation results show that the lowest BER and low NF were obtained, when using the forward pumping configuration. Moreover, we have also compared ASE noise powers of the simulation with this experiment. These results conclude that DRA with low pump power (<1 W) is the promising key technology for short- and/or middle-distance DWDM transmission networks.

KEYWORDS
amplified spontaneous emission (ASE); Dense-wavelength-division-multiplexing (DWDM); DRA (distributed Raman amplifier)

1. Introduction

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

The distributed Raman amplifiers (DRA) based on SRS effect is used popular in the contemporary submarine and long-haul terrestrial networks due to 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 hybrid EDFA and DRA [4]. However, such an optical amplifier also generates amplified spontaneous emission (ASE) noise [5], which will limit the 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 the distributed Raman amplification technology have been reported, but so far, there are very few, neither 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 the proposed architecture, we analyze the effects of the ASE noise on the performance of DWDM networks using the low-power pumped DRA.

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

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 the ith channel in the 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, SRS, 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)–(3) [6–10]:

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

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

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

where g_R is the Raman gain efficiency in $\mathrm{W}^{-1}\mathrm{km}^{-1}$ of the fiber normalized with respect to the effective area $A_{\mathrm{eff}} = \pi r^2$ of the fiber, α_p , α_{si}, and α_n are the attenuation coefficients in km^{-1} at the pump, the ith WDM component of the signal and noise frequencies (f_p, f_{si}, and f_n), and γ is the the Rayleigh backscattering coefficient in km^{-1}.

The first two terms in these equations are fiber loss and Rayleigh backscattering, the last two terms in Equation (1) refer to the signal and the ASE noise induced pump depletion. The third and fourth terms in Equation (2) include stimulated and spontaneous Raman amplification. The last term in Equation (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 [6] in two following pumping configurations.

2.1. *Forward pumping*

In the forward pumping case, signal and pump waves are propagated from $z = 0$ to $z = L$ in $+z$ direction. The differential equations are solved by the analytical method without pump depletion at point z as in [9].

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

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

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

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

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

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

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

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 [9]

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

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

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

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

where

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

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

$$\sigma_{\text{total}}^2 = \sigma_{th}^2 + \sigma_{\text{shot}}^2 + \sigma_{\text{beat}}^2. \quad (16)$$

First, the variance of the thermal noise can be written as

$$\sigma_{th}^2 = \frac{4K_B TB}{R_L}, \quad (17)$$

where K_B is Boltzman's constant, T is the receiver temperature, B is the bit rate, and R_L is the load resistance.

Next, the variance of the shot noise, which is generated by signals, and ASE, is given by

$$\sigma_{\text{shot}}^2 = 2qBI_{\text{signal}} + 2qBI_{\text{ASE}}, \quad (18)$$

where

$$I_{\text{signal}} = P_{\text{signal}} \frac{q}{hf} \quad (19)$$

$$I_{\text{ASE}} = 2n_{sp}(G-1)qB. \quad (20)$$

The last one is the beat noise current. It consists of the signals–ASE beat noise, the ASE–ASE beat noise (beating between the spectral components of the added amplifier ASE), and the signal–signal beat noise. The variance of the beat noise is given by [11,12]

$$\sigma_{\text{beat}}^2 = 2GI_{\text{signal}}I_{\text{ASE}}\frac{B}{B_{\text{opt}}} + \frac{1}{2}(I_{\text{ASE}})^2\frac{B(2B_{\text{opt}}-B)}{B_{\text{opt}}^2} + \frac{1}{2}(GI_{\text{signal}})^2\frac{B(2B_{\text{opt}}-B)}{B_{\text{opt}}^2}. \quad (21)$$

Figure 1 shows noise power as a function of the transmitted power for bit rate of 10 Gbps, 16 channels, optical bandwidth of 0.4 nm and optical amplifier gain of 11 dB. The noise terms contributing significantly to σ_{total}^2 are drawn separately. The beating of the signal–signal and the signal–ASE clearly dominate all other noise terms. It can be said that the ASE noise has a significant impact on the performance of the DWDM system.

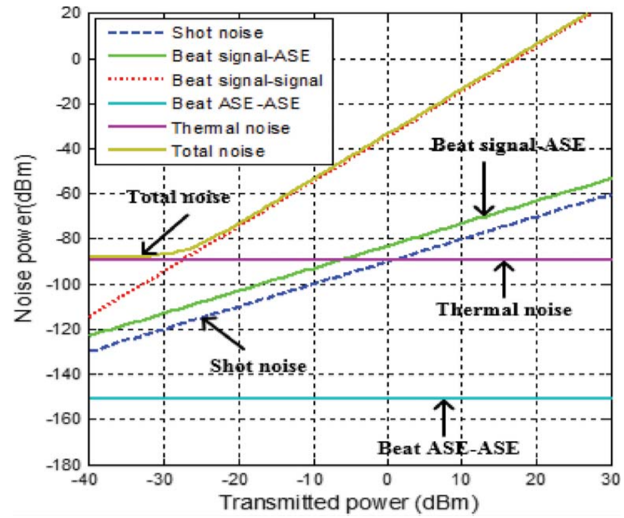

Figure 1: Noise power vs. transmitted optical power, 10 Gbps, $G = 11$ dB, channel space = 0.4 nm.

Finally, the BER can be calculated as

$$\text{BER} = \frac{1}{2}\text{erfc}(\text{SNR}), \quad (22)$$

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

$$\text{SNR} = \frac{I_{\text{signal}}(i\text{th})}{\sigma_{\text{total}}\sqrt{2}}, \quad (23)$$

where $I_{\text{signal}}(i\text{th})$ is the photocurrent of the 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 experiment results [12]. In this model, we used a DRA with different pump configurations, which are forward and backward pumping directions. Figure 2 shows the system with the propagation of 16 DWDM channels located between 193.1 and 193.85 THz, 50 GHz spaced to each other, and a pump wavelength of 1470 nm. A pseudo-random binary sequence (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. On–off-key modulation between an non-return-to zero (NRZ) signal and a CW laser source is carried out by using a Mach–Zehnder modulator. Signals are multiplexed at a multiplexer and then they are combined with

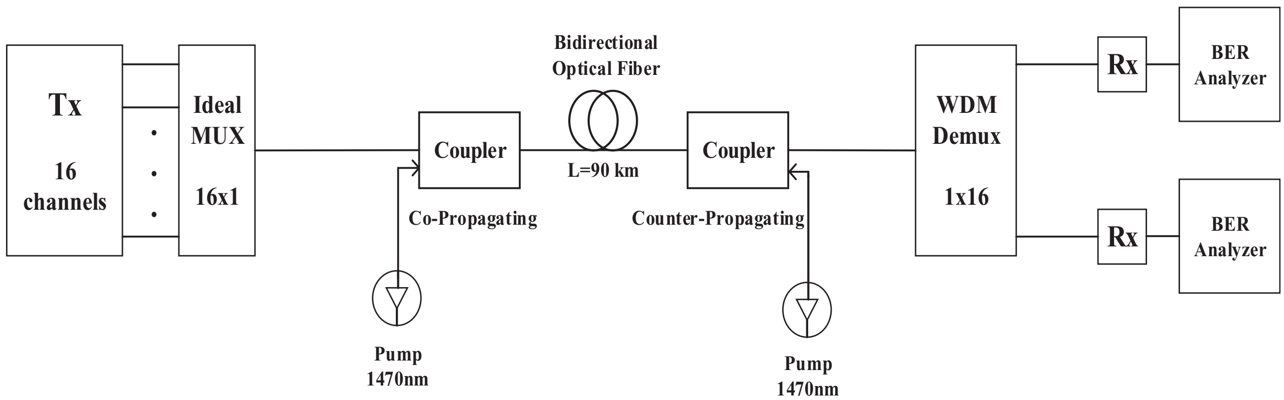

Figure 2: Block diagram of a DWDM system using the distributed Raman amplifier.

the pump at a WDM coupler that transmits them into the bi-directional single-mode optical fiber in the same direction, it is called the forward pumping scheme. On the other hand, when a pump laser is located at the output of the optical fiber, it is called counter or backward pumping. The signal then will be amplified by the SRS effect in a single-mode fiber medium. In the receiver side, the signal is converted into photocurrent by using a positive-intrinsic-negative (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 the ASE noise, NF, and chromatic dispersion on performance of network in different pump configurations. Key parameters used for this simulation are listed in Table 1.

Figure 3 shows forward and backward noise powers as a function of the amplifier length of the first signal channel (193.1 THz) when $P_s = -10\,\text{dBm}$ and $P_p = 880\,\text{mW}$. 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.

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	10 Gbps
Signal frequency	f_s	193.1−193.85 THz
Pump wavelength	λ_p	1470 nm
Pump power	P_p	880 mW
Dispersion chromatic	D	14, 15, 16 ps/nm.km

Figure 4 shows the NF as a function of the DRA amplifier length for forward and backward pumping. We can see that, when the amplifier length is short, the NFs of both pumping configurations are the same. However, when the amplifier length is increased, the NFs are clearly different due to the noise accumulation along the length of the fiber. In addition, the NF is not changed when the length of the amplifier increases in the forward pumping configuration, but this one increases quickly in the backward pumping.

In Figure 5, we fix dispersion the chromatic coefficient$D = 16\,\text{ps/nm.km}$ and the amplifier length of 90 km and investigate the BER vs. signal transmitted power with and without the ASE noise in forward and backward pumping configurations. It is seen that the influence of ASE on the BER increases in the backward pumping case. In detail, the power penalty due to the ASE noise at BER 10^{-9} is about 2 dB for forward

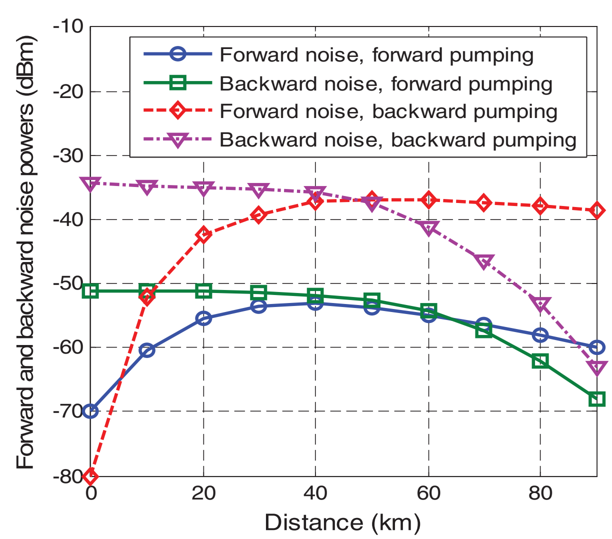

Figure 3: Noise powers as a function of amplifier length (L) with $P_s(0) = -10$ dbm, $P_p = 880$ mW.

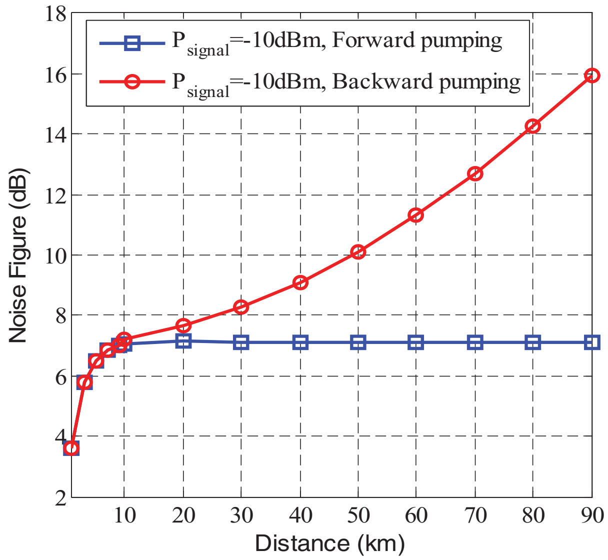

Figure 4: Noise figure as a function of DRA amplifier length (L) with $P_s(0) = -10$ dbm, $P_p = 880$ mW .

pumping, while this one is about 2.3 dB in backward pumping. This result is consistent with the calculation result from Equations (6), (7), (13), (14), where the ASE noise powers in backward pumping are greater than in forward pumping.

3.3. *Experiment results*

Experiments have been carried out on the DWDM network, which is operated at 10 GB/s (Figure 6). As no extra-high power pump source was available, we used three low power pump lasers which emitted a light at a wavelength of 1470 nm. The total pump power is of 880 mW obtained through an optical power combiner.

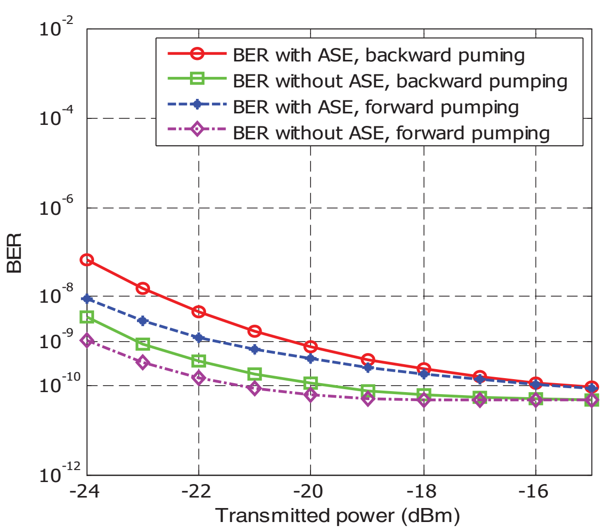

Figure 5: BER vs. transmitted power with Rb = 10 Gbps, D = 16 ps/nm.km, L = 90 km.

Figure 6: Raman amplifier on the DWDM system.

In this system, we used 1480/1550 WDM coupler for coupling pump power into the fiber where signals pass through it [13].

Figure 7 shows the results obtained from the experiment and simulation for optical signal-noise-ratio (OSNR) in backward pumping case as measured at the output of the optical Raman amplifier. As we can see, when no pump signal is injected into the fiber, the OSNR is maximized. Then, the OSNR reduces exponentially in both cases for pump power <200 mW. This is because the pump power over this range is weak and not capable to compensate for losses in the signal, as it propagates through the fiber. The signal power decreases while the pump power is

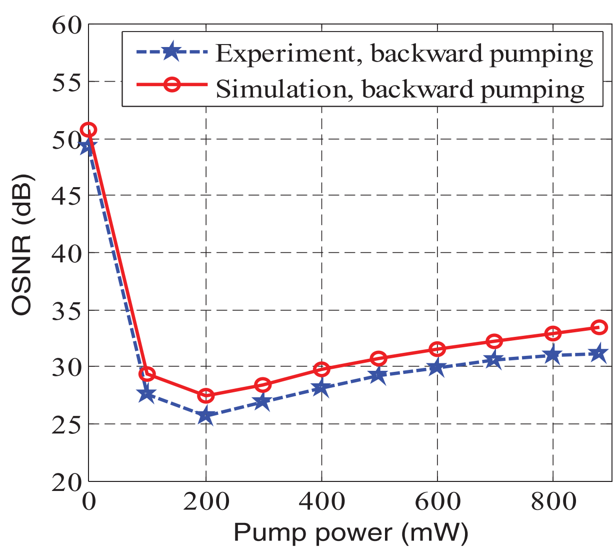

Figure 7: OSNR as a function of pump power, backward pumping.

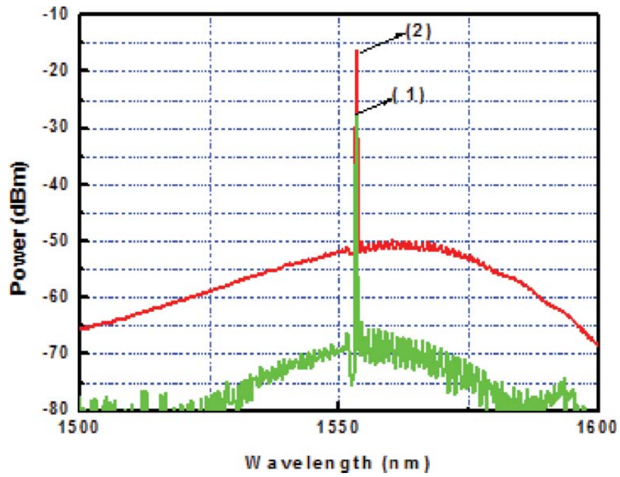

Figure 8: Signal without (curve 1) and with optical gain (curve 2) for $L = 90$ km and $P_p = 880$ mW.

very low which results in decreasing the OSNR. When the pump power was greater than 200 mW, the OSNR gradually increased in both the experiment and the simulation case. However, at pump power above 800 mW in the experiment case the OSNR tended to degrade, this is because double Rayleigh scattering is more evident at higher pump powers especially in the backward pumping. This effect has not been examined in the simulation scenario, thus two cures are not the same.

Figure 8 shows a signal spectrum at a wavelength of 1552.52 nm and the related signal power in the case of Raman amplification in comparison with non-amplification. It can be seen that the signal is amplified up to 11 dB but the bandwidth and the wavelength are not changed. However, the OSNR of the amplified signal is of 31 dB, which is decreased on 6 dB in comparison with the non-amplified one (37 dB). This result shows that the total noise $\sigma^2{}_{\text{total}}$ is increased about 15 dB by the ASE-beat noise, when the thermal and shot noise are the same in an experimental condition. The calculation result of noise power and SNR by formulas (16, 23) is depicted in Figure 1 and the above simulation results very well agree with this experiment result. Moreover, we find that the ASE noise power of the experiment is 2 dB greater than one of the simulations because we do not examine the effect of double Rayleigh scattering and nonlinear effects.

4. Conclusion

We have analyzed the theory and simulated a DWDM network system using a low-power pumped DRA in two different pump configurations. Moreover, we analyzed the effects of the ASE noise and NF on the performance of the DWDM-based system. We found that the different pumping configurations and ASE noise play an important role in network performance. Simulation results show that the low BER and NF were obtained when using the forward pumping configuration for the fiber amplifier length of 90 km. The calculation results are also compared with the experimental one, and they are well matched. In addition, the amplification of DRA depends on both power and wavelength pump. From this study, we conclude that DRA with low-power pump (<1 W) is the promising key technology for short- and/or middle-distance DWDM transmission networks.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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