# The application of distributed Raman amplification in an all optical network

**Xiaoping Zheng (郑小平), Feifei Feng (奉飞飞), Hanyi Zhang (张汉一), and Yanhe Li (李艳和)**

*Department of Electronic Engineering, Tsinghua University, Beijing 100084*

Received October 21, 2002

The effect of distributed Raman amplification (DRA) on the optical signal to noise ratio (OSNR) of an all optical network (AON) is examined by analyzing two types of node isolated principal (NIP). Based on the parameters used in calculation, it is found that in the first case of NIP, the OSNR of a signal passing through such AON can be improved by about 8 dB compared with no DRA. Whereas in the second case of NIP, the OSNR of the signal can be reduced by 11 dB. This kind of phenomena is analyzed and attributed to the dependence of noise figure of amplification system on the way of the active amplification utilization.

*OCIS codes:* 190.5650, 060.4250, 060.2300.

All optical networks (AONs) based on dense wavelength division multiplexed (DWDM) transmission and wavelength routing have attracted great research efforts because of their ability to provide high capacity, flexibility, transparency, and scalability[1]. Optical cross connect (OXC) and optical add/drop multiplexer (OADM) are two essential network nodes in DWDM optical networks[2-3]. Figure 1 shows an OXC with OADM function which typically consists of preamplifiers (EDFA1), demultiplexers, switches for cross connection or adding and dropping, multiplexers and booster amplifier (EDFA2). Amplified spontaneous emission (ASE) noise inside the pass-band of demultiplexer/multiplexer pair due to the erbium-doped fiber amplifiers (EDFAs) accumulates and eventually degrades the optical signal-to noise ratio (OSNR) and limits the number of cascaded OXCs or OADMs[4].

To enlarge the scale of an optical network, distributed Raman amplification (DRA) is a promising technology to greatly reduce the fiber loss and provide a high OSNR throughout the network without increasing the fiber input power[5].

For analyzing the OSNR of the cascaded optical nodes, node isolated principal (NIP) is always used. In this paper, we analyze two typical kinds of the NIP and present a signal to noise ratio analysis of an AON with DRAs. It is shown that DRA can effectively increase OSNR in the AON with one kind of NIP and dramatically decrease OSNR of the AON in another kind of NIP.

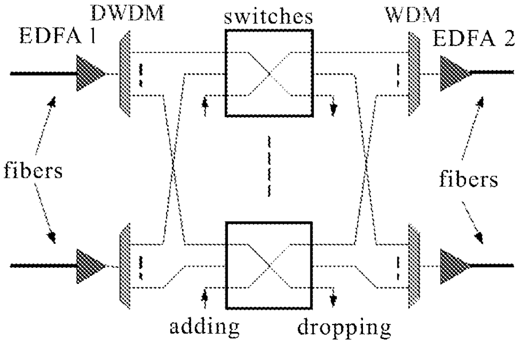

Fig. 1. Schematic diagram of OXC/OADM.

The analyzed AON configuration is shown in Fig. 2. We consider an optical signal passing through n nodes. Between two adjacent nodes, there is a span of transmission fiber that is backward pumped in order to obtain a Raman gain $G_{\mathrm{Raman}}$. According to the NIP, the signal power at EDFA2 output of each node is equal, which means

$$G_{\mathrm{Raman}} L_{\mathrm{fiber}} G_{\mathrm{EDFA1}} L_{\mathrm{node}} G_{\mathrm{EDFA2}} = 1, \tag{1}$$

where $L_{\mathrm{fiber}}$, $L_{\mathrm{node}}$ are the transmission coefficients for the transmission fiber and the optical node, and $G_{\mathrm{EDFA1}}$, $G_{\mathrm{EDFA2}}$ are the gains coefficients obtained by EDFA1 and EDFA2. A Raman pump with the proper power level is injected to get the required gain coefficient $G_{\mathrm{Raman}}$.

Equation (1) sets the value of 1 but leaves individual gains undetermined, so it may lead to two typical types of NIP. In the first type, Raman amplification together with EDFA1 compensates for the loss in the transmission fiber and EDFA2 does for the loss in the node. In this case, Eq. (1) can be divided into two equations: $G_{\mathrm{Raman}} L_{\mathrm{fiber}} G_{\mathrm{EDFA1}} = 1$ and $L_{\mathrm{node}} G_{\mathrm{EDFA2}} = 1$. In the second type, Raman amplification together with EDFA2 compensates for the loss in the transmission fiber and EDFA1 does for the loss in the node. In this case, Eq. (1) can be divided into: $G_{\mathrm{Raman}} L_{\mathrm{node}} G_{\mathrm{EDFA2}} = 1$ and $L_{\mathrm{fiber}} G_{\mathrm{EDFA1}} = 1$. According to Eq. (1), there may be some more types of NPI, we here only choice two typical types because they are enough to show our conclusion.

No matter which type of NSI is, we can get the power of ASE received at dropping port[6]

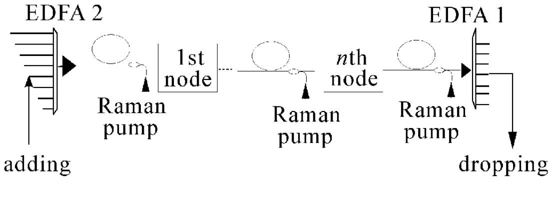

Fig. 2. The analyzed system.

$$\begin{aligned}P_{\rm ASE} = \{[(&NF_{\rm EDFA2}G_{\rm EDFA2}-1)\\ &+n(NF_{\rm span}-1)]G_{\rm Raman}L_{\rm fiber}G_{\rm EDFA1}L_{\rm DM}\\ &+(NF_{\rm Raman}G_{\rm Raman}L_{\rm fiber}-1)G_{\rm EDFA1}L_{\rm DM}\\ &+(NF_{\rm EDFA1}G_{\rm EDFA1}-1)L_{\rm DM}\}h\nu B,\end{aligned}\tag{2}$$

where $L_{\rm DM}$ is the transmission coefficient for demultiplixer, $h, \nu$ and $B$ are Plank constant, the frequency of the signal and detected bandwidth of ASE, respectively. $NF_{\rm EDFA2}$, $NF_{\rm span}$, $NF_{\rm Raman}$ and $NF_{\rm EDFA1}$ are noise figures for EDFA2, span, Raman amplification and EDFA2, respectively. And the power of signal at dropping port is

$$P_{\rm dropping} = P_{\rm adding}L_{\rm mux}G_2G_{\rm Raman}L_{\rm fiber}G_{\rm EDFA1}L_{\rm DM},\tag{3}$$

where $P_{\rm adding}$ denotes the signal power at adding port, and it is reasonable to think $L_{\rm mux}G_2G_{\rm Raman}L_{\rm fiber}G_{\rm EDFA1}L_{\rm DM}$ equal to 1 because $L_{\rm mux}L_{\rm DM}$ can be considered as the transmission coefficient of the node if we take the power equalization module of the node into account. In this case, $L_{\rm mux}$ of an adding signal is corresponding to the product of transmission coefficient of switch matrix and multiplexer. Thus according to NPI, we have $P_{\rm dropping} = P_{\rm adding}$, then at the dropping port the OSNR of the signal is

$$\begin{aligned}\frac{1}{\rm OSNR} &= \left(\frac{P_{\rm dropping}}{P_{\rm ASE}}\right)^{-1} =\\ &\frac{h\nu B}{P_{\rm adding}}\{[(NF_{EDFA2}G_{EDFA2}-1)\\ &+n(NF_{span}-1)]G_{\rm Raman}L_{\rm Fiber}G_{\rm EDFA1}L_{\rm DM}\\ &+(NF_{\rm Raman}G_{\rm Raman}L_{\rm fiber}-1)G_{\rm EDFA1}L_{\rm DM}\\ &+(NF_{\rm EDFA1}G_{\rm EDFA1}-1)L_{\rm DM}.\end{aligned}\tag{4}$$

For the calculation of OSNR improvement with Raman amplification, we assume that the loss of fiber is 25 dB, the loss of node is 15 dB (e.g. 4 dB for a wavelength multi/demultiplexer and 7 dB for a matrix switch), the number of node is 10, and noise figures for both EDFA1 and EDFA2 are 6 dB. In the first case of NIP, the OSNR improvement with the Raman gain is shown in the Fig. 3.

Based on the same calculation parameters, we get the OSNR degradation in the second case of NIP, as shown in the Fig. 4. Comparing the two figures, we find that completely different results are achieved for different types of NIP. In the first case, when the gain of Raman amplification increases from 0 dB to 25 dB, the OSNR improvement of the signal passing through 10 such nodes correspondingly increases from 0 dB to about 8 dB. Whereas, in the second case, when the gain of Raman amplification also increases from 0 dB to 25 dB, the OSNR of the signal passing through the same nodes does not be improved but degraded by more than 11 dB.

Why do different types of NIP lead to different results? We can rewrite Eq. (2) as

$$P_{\rm ASE} = (NF_{\rm trail}-1)h\nu B,\tag{5}$$

where $NF_{\rm trail}$ denotes the total noise figure along the optical path. In the first case of NIP, $NF_{\rm trail}$ can be expressed according to Eq. (2) as

$$\begin{aligned}NF_{\rm trail} = &\frac{NF_{\rm EDFA2}}{L_{\rm mux}} + \frac{n+1}{L_{\rm mux}G_{\rm EDFA2}}(NF_{\rm Raman}-1)\\ &+\frac{n}{L_{\rm mux}G_{\rm EDFA2}}\frac{NF_{\rm node}-1}{G_{\rm Raman}L_{\rm fiber}}\\ &+\frac{NF_{\rm EDFA1}-1}{L_{\rm mux}G_{\rm EDFA2}G_{\rm Raman}L_{\rm fiber}}+1-L_{\rm DM}.\end{aligned}\tag{6}$$

$NF_{\rm trail}$ changes only with Raman gain and noise figure of Raman amplification when other parameters in the right side of Eq. (6) are unchanged. The relationship between $NF_{\rm Raman}$ and Raman gain is plotted in the Fig. 5, and shows that with the Raman gain increasing, $NF_{\rm Raman}$ decreases. Meanwhile, with the Raman gain increasing, both the third and the fourth terms of the right side of Eq. (6) will decrease. Hence the final $NF_{\rm trail}$ will decrease with the increase of Raman gain when the rest terms in the right side of Eq. (6) remain unchanged. According to Eq. (5), the ASE power will certainly decrease with DRA's gain, so the OSNR is improved.

Equation (6) is also valid for the second case of NIP, but it is difficult to understand the result of second type

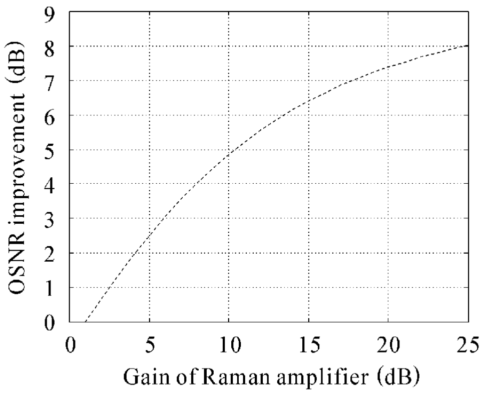

Fig. 3. OSNR improvement in the case of the first NIP.

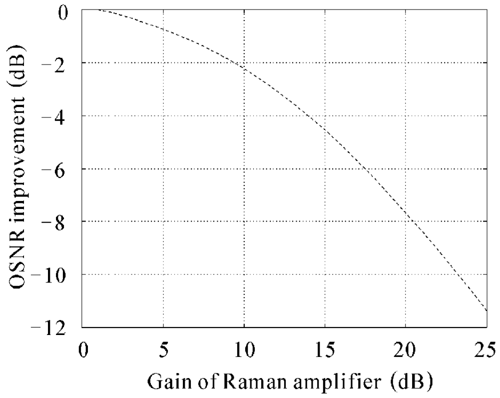

Fig. 4. OSNR degradation in the case of the second NIP.

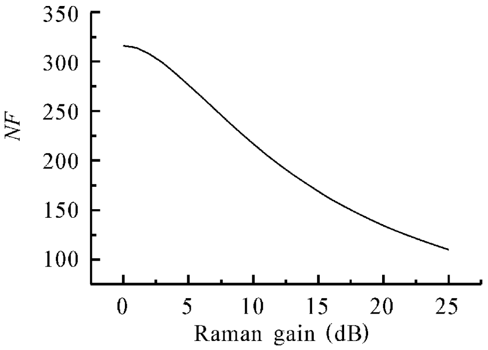

Fig. 5. Raman gain vs $NF$.

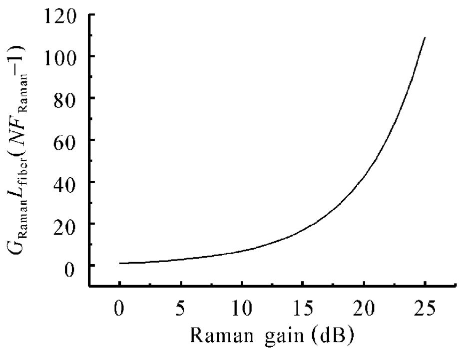

Fig. 6. Raman gain vs $G_{\text{Raman}}L_{\text{fiber}}(NF_{\text{Raman}}-1)$.

of NIP with Eq. (6). In fact, in this case we can change $NF_{\text{trail}}$ expression of Eq. (6) into

$$NF_{\text{trail}}=\frac{(n+1)}{L_{\text{mux}}}[NF_{\text{EDFA2}}-1 +G_{\text{Raman}}L_{\text{fiber}}(NF_{\text{Raman}}-1)] +\frac{n}{L_{\text{mux}}}(NF_{\text{EDFA1}}-L_{\text{node}}) +\frac{NF_{\text{EDFA1}}}{L_{\text{mux}}}+1-L_{\text{DM}}. \quad (7)$$

It is clear that $NF_{\text{trail}}$ depends only on the term $NF_{\text{EDFA2}}+G_{\text{Raman}}L_{\text{fiber}}(NF_{\text{Raman}}-1)$, which is the effective noise figure of cascaded EDFA2 and Raman amplification. When Raman gain increases, the effective noise figure increases as shown in Fig. 6, which brings about the increase of ASE power and the degradation of OSNR.

This work was supported by the National Natural Science Foundation of China under the Grant No. 69990540 and 863 project. X. Zheng's e-mail address is xpzheng@mail.tsinghua.edu.cn.

## References

1. I. P. Kaminow, C. R Doerr, C. Dragone, T. Koch, U. Koren, A. A. M. Saleh, A. J. Kirby, C. M. Özveren, B. Schofield, R. E. Thomas, R. A. Barry, D. M. Castagnozzi, V. W. S. Chan, B. R. Hemenway, Jr., D. Marquis, S. A. Parikh, M. L. Stevens, E. A. Swanson, S. G. Finn, and R. G. Gallager, IEEE J. Select. Areas Comm. **14,** 780 (1996).
2. E. Iannone and R. Sabella, J. Lightwave Technol. **14,** 2184 (1996).
3. R. E. Wagner, R. C Alferness, A. A. M. Saleh, and M. S. Goodman, J. Lightwave Technol. **14,** 1349 (1996).
4. N. Antoniades, I. Roudas, R. E. Wagner, and S. F. Habiby, IEEE Photon. Technol. Lett. **9,** 1274 (1997).
5. T. Watanabe, F. Kan, S. Kuwano, H. Suzuki, and M. Koga, IEEE Photon. Technol. Lett. **12,** 1420 (2000).
6. E. Desurvire, ***Erbium-Doped Fiber Amplifiers: Principles and Applications*** (Wiley Inter Science, New York 1994).