The final limitation of receiver terminal performance with remotely pumped preamplifiers

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In this paper, the performance of receiver terminals with remotely pumped preamplifiers (RPPAs) is analyzed by numerical simulation and experiment. Both simulation and experiment show that there is an optimal RPPA location and optimal pump power according to the highest performance. The amplified spontaneous Raman scattering (ASRS) self-oscillation caused by Rayleigh backscattering (RBS) and the lump reflector in transmission line are the final performance limitation.

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Non-repeated optical systems are usually used in domestic submarine networks[1]. From 1990s, the transmission distance, capacity and performance of non-repeated systems are improved greatly by combination of erbium-doped fiber amplifier (EDFA) and Raman amplification. Remotely pumped preamplifier (RPPA) is a key technology to improve the performance of receiver terminals used in non-repeated systems[2]. Recently, thanks to the development of high power 14xx pump source[3], it is possible to utilize RPPAs to the greatest extent and find the final performance limitations of the receiver terminals with RPPAs.

In our earlier work, the amplified spontaneous Raman scattering (ASRS) noise and double Rayleigh backscattering (DRB) noise in backward pumped Raman amplification are analyzed theoretically. An analysis on various kinds of noise term in receiver electrical domain is developed[4]. In this paper, we extend the analysis to receiver terminals with RPPAs. The relations between receiver terminal performance and RPPA parameters such as RPPA pump power and RPPA location are studied by numerical simulation and experiment. The final performance limitations of the receiver terminal with RPPA are discussed.

The most important thing in non-repeated submarine systems is the reliability of transmission line under water. Although more complex RPPA structure maybe has higher performance, the structure shown in Fig. 1 is always the preference in commercial systems because there are no optical components under water. The RPPA is only a section of erbium-doped fiber (EDF), splicing directly with transmission fiber.

Both the EDF in RPPA and EDFA preamplifier are simulated by Giles model[5] with real EDF parameters. The gain and ASRS noise of Raman amplification by RPPA pump can be calculated by iteration using[6]

$$\begin{aligned}
\frac{\mathrm{d}P_f(z,\nu)}{\mathrm{d}z} &= -\alpha(\nu)P_f(z,\nu) + rP_b(z,\nu) \\
&+ \int_{\zeta>\nu} \left\{ C_r(\zeta,\nu)[P_f(z,\zeta)+P_b(z,\zeta)]P_f(z,\nu) + 2h\nu C_r(\zeta,\nu)[P_f(z,\zeta)+P_b(z,\zeta)] \cdot \left[1+\frac{1}{\mathrm{e}^{h(\zeta-\nu)/kT}-1}\right] \right\} \\
&- \int_{\zeta<\nu} \left\{ C_r(\nu,\zeta)[P_f(z,\zeta)+P_b(z,\zeta)]P_f(z,\nu) + 2h\nu C_r(\nu,\zeta)[P_f(z,\zeta)+P_b(z,\zeta)] \cdot \left[1+\frac{1}{\mathrm{e}^{h(\nu-\zeta)/kT}-1}\right] \right\}, \\
\frac{\mathrm{d}P_b(z,\nu)}{\mathrm{d}z} &= -\alpha(\nu)P_b(z,\nu) + rP_f(z,\nu) \\
&+ \int_{\zeta>\nu} \left\{ C_r(\zeta,\nu)[P_f(z,\zeta)+P_b(z,\zeta)]P_b(z,\nu) + 2h\nu C_r(\zeta,\nu)[P_f(z,\zeta)+P_b(z,\zeta)] \cdot \left[1+\frac{1}{\mathrm{e}^{h(\zeta-\nu)/kT}-1}\right] \right\} \\
&- \int_{\zeta<\nu} \left\{ C_r(\nu,\zeta)[P_f(z,\zeta)+P_b(z,\zeta)]P_b(z,\nu) + 2h\nu C_r(\nu,\zeta)[P_f(z,\zeta)+P_b(z,\zeta)] \cdot \left[1+\frac{1}{\mathrm{e}^{h(\nu-\zeta)/kT}-1}\right] \right\}, \quad (1)
\end{aligned}$$

where $P_f(z,\nu)$ and $P_b(z,\nu)$ are the forward or backward light power in location z at frequency ν, $\alpha(\nu)$ is fiber loss, r is Rayleigh backscattering (RBS) coefficient, C_r is the Raman gain coefficient between lights with frequency ν and ζ. h is the Plank constant, k is the Bolzman constant and T is the absolute temperature.

DRB noise can be calculated by extending the result of Ref. [4] to the case of multi-channels and multi-pump

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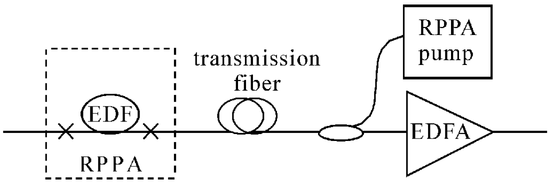

Fig. 1. Structure of receiver terminal with RPPA.

wavelength. The average square noise term of DRB noise is

$$\sigma^2_{\mathrm{DRB}} = \frac{10}{9} r^2 \int_0^L \int_0^{z_2} G(z_1, z_2)^2 \mathrm{d}z_1 \mathrm{d}z_2 \cdot P_{\mathrm{s}} P_{\mathrm{re}} \cdot \eta^2, \qquad (2)$$

where P_{s} is the signal power into receiver, P_{re} is the average value of P_{s} and η is the detector response of the receiver. G is the signal net gain between z_1 and z_2

$$G(z_1, z_2) = \exp\left[\sum_i \int_{z_1}^{z_2} C_r(\nu_{p,i}, \nu) P_{p,i}(z) \mathrm{d}z - \alpha(\nu)(z_2 - z_1)\right], \qquad (3)$$

where $\nu_{p,i}$ and $P_{p,i}(z)$ are the frequency and power distribution along the fibers of i-th pump calculated by Eq. (1).

To describe receiver terminals performance with RPPAs, an extended receiver sensitivity ($P_{\mathrm{RS\_EX}}$) is defined as the signal power before RPPA when BER requirement is equal to a given value (usually 10^{-12}). However, this concept is not suit for comparisons of receiver terminal performances with different RPPA locations. Similar with the analysis in Ref. [4], RPPA, Raman amplification and EDFA preamplifier can be treated as a lump amplifier at the end of transmission fiber, and the sensitivity before the equivalent lump amplifier can be defined as an equivalent receiver sensitivity (ERS). The relation of $P_{\mathrm{RS\_EX}}$ and ERS is $P_{\mathrm{ERS}} = P_{\mathrm{RS\_EX}} - L_{\mathrm{RPPA}}$, where L_{RPPA} is the fiber loss between RPPA and input end of EDFA preamplifier. So ERS also reflects the effect of RPPA location.

In this paper, a single channel 2.5-Gb/s receiver terminal at 1550 nm is considered, parameters shown in Table 1. The RPPA pump wavelength is 1485 nm. Transmission fiber is a piece 100-km long single-mode fiber (SMF), parameters shown in Table 2. The EDF in RPPA is 12 m long. The EDFA preamplifier uses two sections structure, with 36-dB small signal gain and 4.2-dB noise figure.

Table 1. Receiver Parameters

EXT	0.05
Receiver Electrical Bandwidth	0.75 B Rate
Filter Bandwidth before Receiver	50 GHz
Detector Responsivity	0.8
Receiver Thermal Noise	0.036 μA^2
BER Requirement	10^{-15}

Table 2. Transmission Fiber Parameters

1485-nm Loss	0.25 dB/km
1550-nm Loss	0.22 dB/km
Peak C_r	0.4 /(W·km)
r	−40 dB/km

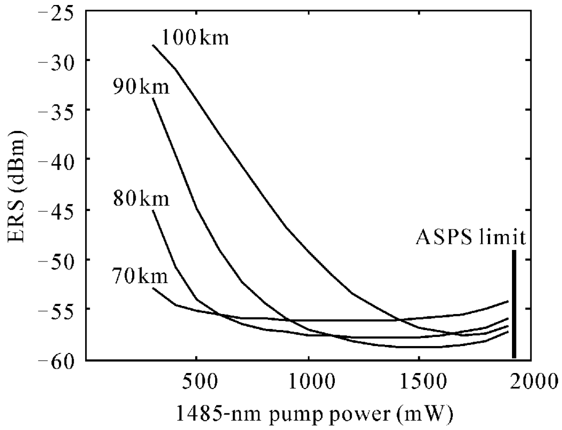

Fig. 2. ERS versus RPPA pump power at different RPPA location.

Figure 2 shows the relationship between ERS and RPPA pump power at different RPPA locations. For a giving RPPA location, the insufficiency of pump power injected into RPPA limits the ERS if the RPPA pump power is low. If pump power is too high, the ERS degrades by RBS in transmission fiber. RBS degrades the noise of Raman amplification in two aspects: ASRS in one direction will be reflected by RBS into the other direction and experience gain, leading to increased noise, even self-oscillation which transfers pump energy to a longer Stokes wavelength; on the other hand, multiple (mainly double) reflection of signal through RBS will cause multipath interference of optical signal at the receiver called DRB noise[4]. In the case of RPPA receiver terminal, the signal is not at the wavelength of Raman gain peak of the RPPA pump (1485 nm), so the ASRS self-oscillation appears earlier than serious penalty by DRB noise as the dominating limitation. Numerical simulations show that Eq. (1) will not reach convergence if the pump power is too high, at the same time a sharp peak appears at ASRS spectrum, denoting that ASRS self oscillation occurs.

In Fig. 2, an optimal pump power according to the best ERS exists at giving RPPA location. If the distance between RPPA and EDFA preamplifier is small, high performance improvement can be achieved at quite low pump power. Further more, the ERS is almost unchanged in a wide range of pump power. As shown in Fig. 2, if the distance between RPPA and EDFA is 70 km, the ERS can be improved to −55 dBm at a pump power of only 500 mW, and the ERS varies within 1.5 dB from 0.5 to 1.3 W pump power. The optimal pump power is 1.1 W according to the best ERS of −56 dBm. As the distance increases, the optimal pump power rises and the best ERS becomes higher. At the same time the ERS at low pump power degrades by insufficiency pump power in RPPA. The optimal distance is 90 km, with the best ERS of −58 dBm according to the optimal pump power 1.5 W and a critical pump selection requirement. If the distance increases farther, higher pump power is required and the best ERS will be worsen by RBS.

From above analysis we can conclude that receiver terminals with RPPAs can be looked upon as a cascaded amplification system, whose performance is dominant by the first amplifier, RPPA. The key of improving performance is moving RPPA forward and making signal light amplified as early as possible in the condition of sufficient pump power injected in RPPA. But ASRS self-oscillation limits the pump power, and gives a final limitation of receiver terminal performance with RPPA.

An experiment is taken to study the relations between receiver terminal performance and RPPA parameters. The experimental setup is shown in Fig. 3. A commercial optical transmitter/receiver unit is used at 622 Mb/s. The EDFA preamplifier has a small signal gain of 35 dB and a noise figure of 4 dB. EDF used in RPPA is 30 m long. A fiber Raman laser is used as RPPA pump with 1 W max output power at 1454 and 1463 nm. 50-km SMF is used as transmission fiber, the residual fiber loss of longer distance between the RPPA and the EDFA preamplifier is compensated by a variable optical attenuator (VOA_1). Another VOA (VOA_2) is used to change input signal power for BER measurement.

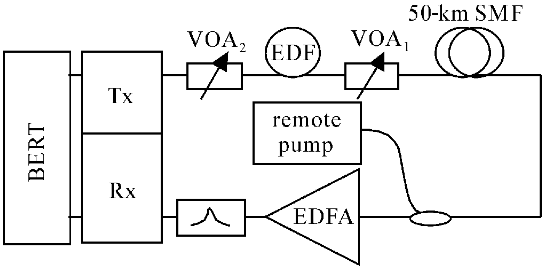

Fig. 3. Experimental setup.

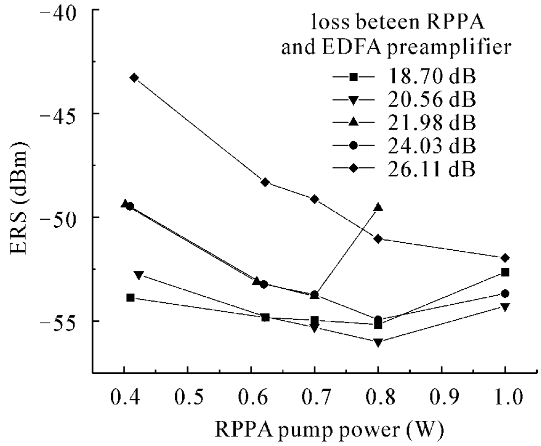

Fig. 4. ERS versus RPPA pump power at different loss between RPPA and EDFA preamplifier.

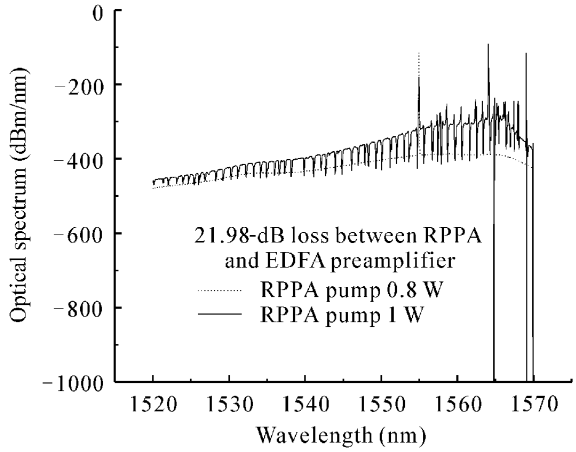

Fig. 5. ASRS self-oscillation.

The ERS measurement result at different RPPA location is shown in Fig. 4. The optimal pump power increases as the loss between RPPA and EDFA rises. At the same time the best ERS improves firstly, then degrades by RBS. These results agree well with Fig. 2. The highest ERS achieved in experiment is −56 dBm, according to 20.56-dB loss between RPPA and EDFA preamplifier and 0.8 W pump power. It is worth to note that the receiver and RPPA pump are not optimized for non-repeated application in this experiment.

In this experiment we also observe ASRS self-oscillation. In Fig. 4, the curve of 21.98-dB loss rises rapidly with pump power. Observing by optical spectrum analyzer at the input end of VOA_1, the ASRS spectrum is unstable and a sharp peak appear at the wavelength of Raman gain peak, showing self-oscillation at a pump power of 1 W in Fig. 5. Since a pump power of 1 W is not high enough, ASRS self-oscillation is enhanced by lump reflection of non-ideal connector at the input end of the EDFA preamplifier. As ASRS self-oscillation is the final performance limitation of receiver performance with RPPA, lump reflectors in transmission line will degrade the limitation greatly.

The performance of receiver terminals with RPPAs is analyzed in this paper. Both simulation and experiment show that there is an optimal RPPA location and optimal pump power according to the highest performance. The ASRS self-oscillation is the final limitation of the highest performance available. The experiment shows that not only RBS in fiber but also lump reflectors in transmission line impact the final limitation of ASRS self-oscillation.

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