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Theoretical analysis on double Rayleigh backscattering noise in optical fibre Raman amplifiers and its suppression*

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In this paper, amplified double Rayleigh backscattering noise (DRB) in the optical fibre Raman amplifier is analysed. Expressions are presented for both forward pumping and backward pumping schemes. Calculation is performed to show the effective suppression of DRB noise by employing an optical isolator. The optimal position for the isolator is determined and is found to be insensitive to the power levels of the signals and pumps. The results show that a reduction of the DRB noise by almost 2 to 3 orders can be reached.

Keywords: optical fibre Raman amplifier, double Rayleigh backscattering
PACC: 4265

1. Introduction

The optical fibre Raman amplifier is of high gain, wide bandwidth, low noise figure and good temperature stability. It has flexible centre wavelength and is applicable to the whole low attenuation window from 1.28 to 1.625nm as long as appropriate pumps are available. Double Rayleigh backscattering (DRB) noise is one of the limitation factors to the performance of the amplifier.[1−3] When the optical signal propagates in the fibre, it generates a Rayleigh backscattering wave (RB).[4] This back scattering wave becomes a forwardly propagating wave when being doubly scattered, which is referred to as double Rayleigh backscattering wave (DRB). DRB will interfere with the signal and produce noise. Because of the distributed amplification effect of fibre Raman amplifiers, DRB will also be amplified significantly. For applications such as long haul systems, DRB degrades the system performance via the accumulated effect.[5] Therefore, it is practically important to reduce DRB. An optical isolator can stop the backscattering signal and then is capable of suppressing the DBR noise.[1] In this paper, the amplified DRB in both a forward- and backward-pumped optical fibre Raman amplifier is analysed along with analytical expressions and simulation results. The results show that amplified DRB can be reduced greatly by use of an inserted optical isolator. Due to the nonlinearity of the Raman amplification, the position of the isolator has a large effect on the suppression efficiency. The determination of optimal position for the isolator is also given.

2. Theory

The quantitative analysis of the noise generated by DRB has been carried out.[1] The expressions can be modified to include the distributed amplification effect of the optical fibre Raman amplifier:

$$P_{\mathrm{DRB}}(z) = 2 \times \frac{5}{9} \times \alpha_r^2 S^2 \times \int_0^z \int_0^{z_2} \mathrm{e}^{-2\alpha_s(z_2-z_1)} G_{\mathrm{RB}} G_{\mathrm{DRB}} \times F\langle |R_{\mathrm{S}}(\tau)|^2 \rangle \mathrm{d}z_1 \mathrm{d}z_2, \quad (1)$$

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where $P_{\mathrm{DRB}}(z)$ is the DRB noise power (see Fig.1). α_{r} and S are the Rayleigh scattering coefficient and recapture factor, respectively. α_{s} is the fibre attenuation coefficient. $|R_{\mathrm{S}}(\tau)|$ is the time-average autocorrelation function of the input signal. $F\langle\rangle$ stands for Fourier transformation. G_{RB} and G_{DRB} are the Raman gain coefficients of the Rayleigh backscattering and double Rayleigh backscattering waves, respectively. In fibre Raman amplifiers, the pump power is much higher than the noise, so the pump depletion due to the DRB noise can be neglected. For forward pumping, these two gains, denoted as G^{+}_{RB} and G^{+}_{DRB}, can be derived from [1,6]

$$\begin{aligned} G^{+}_{\mathrm{RB}}(z_1,z_2) =& \frac{P_{\mathrm{RB}}(z_1)}{P_{\mathrm{RB}}(z_2)} \\ =& \exp\left\{ \frac{g_R P^{+}_{\mathrm{P}}(0)}{\alpha_{\mathrm{s}} A_{\mathrm{eff}}} \exp(-\alpha_{\mathrm{s}} z_1) \right. \\ & \times [\exp(\alpha_{\mathrm{s}}(z_2 - z_1)) - 1] \\ & \left. - \alpha_{\mathrm{s}}(z_2 - z_1) \right\}, \end{aligned} \tag{2a}$$

$$\begin{aligned} G^{+}_{\mathrm{DRB}}(z_2,z_1) =& \frac{P_{\mathrm{DRB}}(z_2)}{P_{\mathrm{DRB}}(z_1)} \\ =& \exp\left\{ \frac{g_R P^{+}_{\mathrm{P}}(0)}{\alpha_{\mathrm{s}} A_{\mathrm{eff}}} \right. \\ & \times [\exp(-\alpha_{\mathrm{s}} z_1) - \exp(-\alpha_{\mathrm{s}} z_2)] \\ & \left. - \alpha_{\mathrm{s}}(z - z_1) \right\}, \end{aligned} \tag{2b}$$

where $P^{+}_{\mathrm{P}}(z)$ and $P_{\mathrm{RB}}(z)$ are the forward pump power and Rayleigh backscattering power, respectively. g_{R} is Raman gain coefficient, A_{eff} is effective core area of the fibre. '+' means forward propagation.

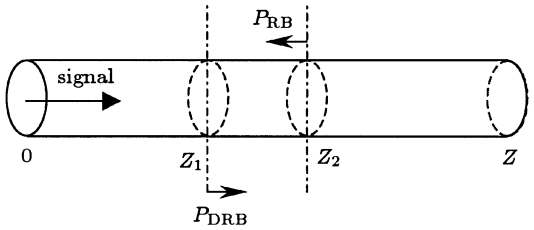


Fig.1. Schematic illustration of signal, RB wave and DRB wave.

For backward pumping, it is very difficult to directly obtain expressions of gain like Eq.(2), due to the counter-propagation property of the signal and the pump. However, by eliminating the pump depletion on the DRB, one can derive the gains of the Rayleigh backscattering and double Rayleigh backscattering waves as follows:

$$\begin{aligned} G^{-}_{\mathrm{RB}}(z_1,z_2) =& \frac{P_{\mathrm{RB}}(z_1)}{P_{\mathrm{RB}}(z_2)} \\ =& \exp\left\{ \frac{g_R P^{-}_{\mathrm{P}}(L)}{\alpha_{\mathrm{s}} A_{\mathrm{eff}}} \exp(-\alpha_{\mathrm{s}} L) \right. \\ & \times [\exp(\alpha_{\mathrm{s}} z_2) - \exp(\alpha_{\mathrm{s}} z_1)] \\ & \left. - \alpha_{\mathrm{s}}(z_2 - z_1) \right\}, \end{aligned} \tag{3a}$$

$$\begin{aligned} G^{-}_{\mathrm{DRB}}(z_2,z_1) =& \frac{P_{\mathrm{DRB}}(z_2)}{P_{\mathrm{DRB}}(z_1)} \\ =& \exp\left\{ \frac{g_R P^{-}_{\mathrm{P}}(L)}{\alpha_{\mathrm{s}} A_{\mathrm{eff}}} \exp(-\alpha_{\mathrm{s}} L) \right. \\ & \times [\exp(\alpha_{\mathrm{s}} z) - \exp(\alpha_{\mathrm{s}} z_1)] \\ & \left. - \alpha_{\mathrm{s}}(z - z_1) \right\}, \end{aligned} \tag{3b}$$

where $P^{-}_{\mathrm{P}}(L)$ is the back-pump power, L is the fibre length. '–' means backward propagation.

As the pump depletion is relatively small in the backward-pumping configuration, the above simplification of ignoring pump depletion due to DRB noise in deriving expressions for the Rayleigh scattering wave gain coefficient is valid. The pump depletion should, of course, be taken into consideration in analysing the signal amplification effect.

The evolution of pump power, signal and DRB in the fibre Raman amplifier is then determined by [7]

$$\frac{\mathrm{d}P_{\mathrm{s}}}{\mathrm{d}z} = \frac{g_{\mathrm{R}}}{2A_{\mathrm{eff}}} P^{\pm}_{\mathrm{P}} P_{\mathrm{S}} - \alpha_{\mathrm{S}} P_{\mathrm{S}}, \tag{4a}$$

$$\frac{\mathrm{d}P^{\pm}_{\mathrm{P}}}{\pm \mathrm{d}z} = \mp \frac{\omega_{\mathrm{P}}}{\omega_{\mathrm{S}}} \frac{g_{\mathrm{R}}}{2A_{\mathrm{eff}}} P^{\pm}_{\mathrm{P}}(P_{\mathrm{S}} + P_{\mathrm{DRB}}) \mp \alpha_{\mathrm{S}} P^{\pm}_{\mathrm{P}}, \tag{4b}$$

$$\begin{aligned} \frac{\mathrm{d}P_{\mathrm{DRB}}}{\mathrm{d}z} =& 2 \times \frac{5}{9} \alpha_{\mathrm{r}}^2 S^2 P_{\mathrm{S}}^2 \\ & \times \int_0^L \int_0^{z_2} \mathrm{e}^{-2\alpha_{\mathrm{S}}(z_2 - z_1)} G^{\pm}_{\mathrm{RB}} G^{\pm}_{\mathrm{DRB}} \mathrm{d}z_1 \mathrm{d}z_2 \\ & - \alpha_{\mathrm{S}} P_{\mathrm{DRB}}, \end{aligned} \tag{4c}$$

where P_{s} is the signal power, ω_{p} and ω_{s} are the pump and signal frequencies, respectively.

In the case of forward pumping, the signal, $P_{\mathrm{s}}(0)$, and the pump, $P^{+}_{\mathrm{P}}(0)$, are coupled into the fibre at z=0. Hence it is relatively easy to solve Eq.(4) numerically because the initial conditions for both signal

and pump are known. In the case of backward pumping, the pump with a power of $P_{\rm P}^{-}(L)$ is coupled into the fibre at $z = L$. There is in fact only one initial condition available. In order to solve Eq.(4) numerically, multiple trials can be employed. The procedure is as follows. Firstly, a forward pump with the same power as $P_{\rm P}^{-}(L)$ and the signal with power of $P_{\rm s}(0)$ are coupled simultaneously into the fibre input end. Their evolution along the fibre is easy to obtain as described above. The output signal power, $P_{\rm s}(L)$, is then taken as the test initial value for trials followed. Secondly, Eq.(4) is solved digitally starting from fibre output end with the above initial values, i.e., $P_{\rm P}^{-}(L)$ for the pump and $P_{\rm s}(L)$ for the signal. The resulting signal power at the fibre input end, $P_{\rm s}'(0)$, is then compared with $P_{\rm s}(0)$. If $P_{\rm s}'(0)$ is bigger than $P_{\rm s}(0)$, a new trial is performed with reduced signal initial value at $z = L$. Otherwise, signal initial value at $z = L$ will be enlarged. The trials continue until $P_{\rm s}'(0) = P_{\rm s}(0)$. Then one obtains the distribution of the forward signal and back-pump. The solution takes the pump depletion on signal into consideration and is rigorous.

Because of the distributed amplification effect, DRB in the fibre Raman amplifier is much larger than that in an ordinary transmission system of the same length. An optical isolator can be inserted into the Raman fibre amplifier to stop the backward Rayleigh scattering and, hence, reduce DRB. An optical isolator allows the forward wave to pass with a small insertion loss of about 0.3dB. It stops, however, the backscattering wave. Therefore, the integral length in the above expressions is broken into two sections. The DRB noise power should be integrated in each section respectively. The output DRB noise power is the superposition of the ones from section 1 (referred to as DRB1) and section 2 (referred as DRB2). In calculating the contribution of DRB1 at the fibre output end, the further Rayleigh scattering effect of DRB1 in section 2 can be ignored because it is much less than the signal power. However, the Raman amplification effect has to be taken into consideration.

3. Results and discussion

Due to the nonlinear procedure of DRB generation, the effectiveness of DRB noise suppression is dependent strongly on the position of the isolator. Figures 2 and 3 show the relationship between the output DRB noise and the position of the isolator for different signal and pump level with forward-pump and backward-pump, respectively. The parameters used are L=40km, $g_{\rm R} = 1 \times 10^{-13}$m/W, $\alpha_{\rm S}$=0.2dB/km, $\alpha_{\rm r} = 3.2 \times 10^{-2}$/km, $S = 1.5 \times 10^{-3}$, $A_{\rm eff}$=55μm^2, $\lambda_{\rm S}$=1550nm. It can be seen that there is a range of optimal isolator position about 10 to 15 kilometres from the input end for forward pumping, and 5 to 10 kilometres from the output end for backward pumping. The optimal position is almost independent of the signal and pump levels. We also calculated the extreme cases that the pump is zero or very large (e.g. more than 2W), and found this feature of optimal isolator position still holds. The only change is that the optimal range becomes narrower and closer to the pumping end as the pump power increases.

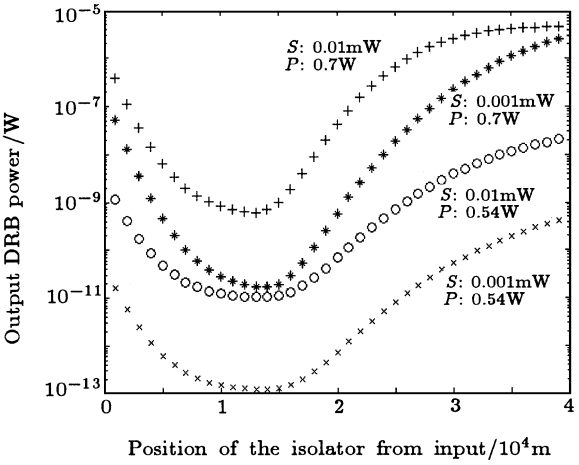


Fig.2. The relationship between the output DRB power and the position of the optical isolator for different signal power and different forward pump power (S—signal power, P—pump power).

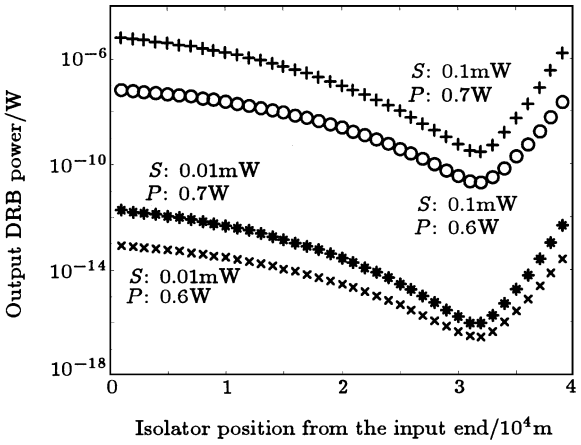


Fig.3. The relationship between the output DRB power and the position of the optical isolator for different signal power and different backward pump power (S—signal power, P—pump power).

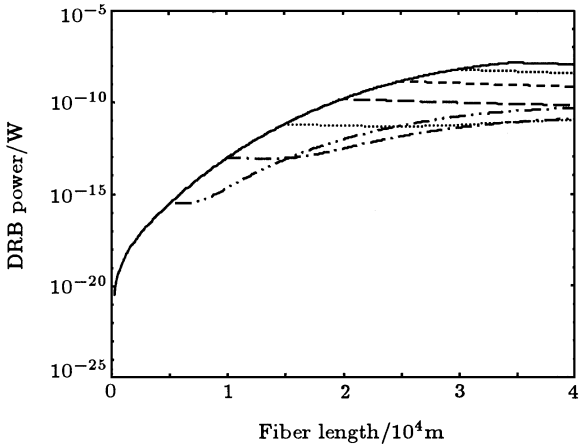


Fig.4. DRB power evolution along the fibre length for different isolator position (forward pumping).

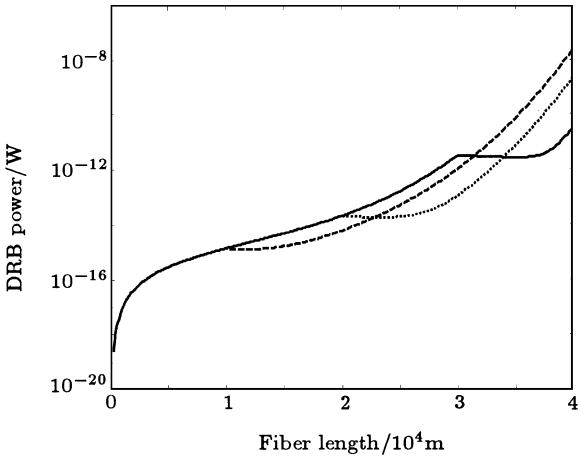


Fig.5. DRB power evolution along the fibre length for different isolator position (backward pumping).

Figures 4 and 5 show the DRB noise along the fibre length of the amplifier for different isolator positions with forward-pump and backward-pump, respectively. The turning point in the figures indicates the position of the optical isolator. The results show that the insertion of the isolator can effectively reduce the DRB noise by almost 2 to 3 orders.

4. Conclusion

In conclusion, we have analysed the DRB noise in the forward-pumped and backward-pumped optical fibre Raman amplifiers. Calculation is performed to show the effective suppression of this kind of noise by employing an optical isolator. The results show that there is a relatively insensitive range of optimal isolator position, which is about 10 to 15 kilometres away from the input end for forward pumping and 5 to 10 kilometres away from the output end for backward pumping, regardless the power levels of the signals and pumps. The method can effectively reduce the DRB noise by almost 2 to 3 orders.

References

[1] Wan P and Conradi J 1996 *J. Lightwave Technol.* **14** 288
[2] Xu W C, Zhang S M, Chen W C *et al* 2002 *Chin. Phys.* **11** 39
[3] Hansen P B, Eskildsen L, Stentz A J *et al* 1998 *IEEE Photon. Technol. Lett.* **10** 159
[4] Brinkmeyer E 1980 *Electron. Lett.* **16** 329
[5] Wan P and Conradi J 1995 *Electron. Lett.* **31** 383
[6] Mochizuki Kiyofumi 1985 *J. Lightwave Technol.* **LT-3** 688
[7] Agrawal G P 1995 *Nonlinear Fiber Optics* 2nd edn (New York: Academic)