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Behaviour of a wideband double-pass discrete Raman amplifier with simultaneous reflection of signals and multi-pump*

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The behaviour of a high efficient double-pass discrete Raman amplifier with 80nm bandwidth was studied theoretically and experimentally. In this Raman amplifier, by using a one-end gilt fibre as the broadband reflector, signals and multi-pump are simultaneously reflected to propagate through the gain fibre for a second time in the opposite direction of the input. An increase in net gain of more than 150% has been achieved compared with that in the typical co-pumped Raman amplifier. The advantages of this new configuration have been studied by comparing with the currently existing Raman amplifier configurations. Also, the influencing factors for the gain increase have been analysed, including the pump-to-pump Raman interactions and the length of gain fibre.

Keywords: discrete Raman amplifiers, double-pass, reflection, net gain
PACC: 4280S, 4280

1. Introduction

Raman amplifiers (RA) with multi-pump have drawn significant attention due to their wide- and flat-gain profile and excellent signal-to-noise ratio (SNR) performance in WDM systems.[1−5] Because of the wavelength independence of Raman gain, discrete Raman amplifiers have potential use in extending new gain bandwidth as S-band or L-band.[6−7] However, owing to the low Raman conversion efficiency, the amplifiers require high-power pump lasers and long gain fibre to achieve enough gain, which results in high cost. Therefore, it is important to enhance the gain efficiency when designing a discrete Raman amplifier.

Typically, Raman amplifiers are operated in the counter-pumped scheme for decreased pump-to-signal crosstalk and polarization-dependent gain. However, with the low-noise pump lasers, co-pumped and bi-directional pumped Raman amplifiers come into use for better noise and SNR performance.[8] The expected increase in gain was achieved in both reflection schemes.[9,10] However, in the reported experiments, only one pump wavelength or one signal wavelength was employed. Besides this, the range of the reflected wavelength is also limited by the stop band width of the FBG reflectors.

In this paper, we proposed a wideband double-pass discrete Raman amplifier based on a one-end gilt fibre, which has a flat reflectivity of more than 93% over the wavelength range of 1420–1620nm. In this proposed wide-band double-pass configuration, all the pumps and the signals covering $C + L$-band are reflected simultaneously (called as the simultaneous double-pass configuration below). Compared with the configurations only reflecting signals or pumps,[9,10] this double-pass configuration has been proved to have an obvious advantage on gain efficiency by the following simulation and experimental results. Also, the influencing factors for the gain increase are studied theoretically and experimentally.

2. Numerical simulation

The configuration of the double-pass Raman amplifier with simultaneously reflecting signals and pumps is shown in Fig.1. The propagation of the signals and the pumps in the amplifier is shown in Fig.2.

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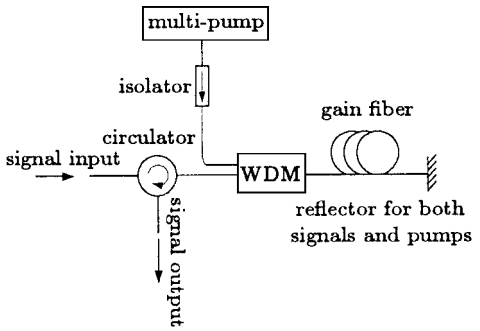


Fig.1. Configuration of the proposed double-pass discrete Raman amplifier.

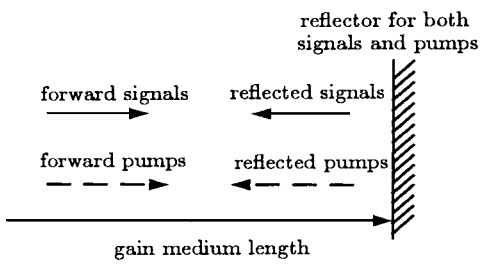


Fig.2. The signals and the pumps in the Raman amplifier.

In the proposed double-pass Raman amplifier with simultaneous reflection of signals and pumps, there are four kinds of lightwaves travelling in the gain medium in the steady state. They are the forward signals, the forward pumps, the reflected backward signals and the reflected backward pumps. The power evolution of these lightwaves can be described by a set of coupled equations as follows:

$$\begin{aligned}\frac{\mathrm{d}P^{\pm}(z,v_i)}{\mathrm{d}z} &= \mp\alpha(v_i)P^{\pm}(z,v_i) \pm \eta(v_i)P^{\mp}(z,v_i)\\ &\pm P^{\pm}(z,v_i)\sum_{m=i+1}^{n}\frac{g_R(v_m-v_i)}{\Gamma A_{\mathrm{eff}}}\\ &\times[P^{\pm}(z,v_m)+P^{\mp}(z,v_m)]\\ &\pm hv_i\sum_{m=i+1}^{n}\frac{g_R(v_m-v_i)}{\Gamma A_{\mathrm{eff}}}\\ &\times[P^{\pm}(z,v_m)+P^{\mp}(z,v_m)]\\ &\times\left[1+\left(\mathrm{e}^{\frac{h(v_m-v_i)}{kT}}-1\right)^{-1}\right]\Delta v\\ &\mp P^{\pm}(z,v_i)\sum_{m=1}^{i-1}\frac{v_i}{v_m}\frac{g_R(v_i-v_m)}{\Gamma A_{\mathrm{eff}}}\\ &\times[P^{\pm}(z,v_m)+P^{\mp}(z,v_m)]\\ &\mp 2hv_iP^{\pm}(z,v_i)\sum_{m=1}^{i-1}\frac{v_i}{v_m}\frac{g_R(v_i-v_m)}{\Gamma A_{\mathrm{eff}}}\\ &\times\left[1+\left(\mathrm{e}^{\frac{h(v_i-v_m)}{kT}}-1\right)^{-1}\right]\Delta v, \qquad (1)\end{aligned}$$

where $P(z,v_i)$ is optical power within infinitesimal bandwidth around v_i, superscripts + and - denote the forward- and the reflected backward-propagating lightwaves, respectively, α is the attenuation coefficient, η is the Rayleigh backscattering coefficient, A_{eff} is the effective area of the optical fibre at frequency v_m, $g_{\mathrm{R}}(v_m-v_i)$ is the Raman gain parameter at frequency v_i due to the pump at frequency v_m, h is Planck's constant, k is the Boltzmann constant, Γ is the polarization scrambling factor between pump and signal light (Γ varies from 1 to 2 and Γ=2 for the depolarized case), and T is the temperature. In this equation, the pump-to-pump Raman interactions (including that between co-propagating and counter-propagating ones), the signal-to-signal Raman interactions, pump depletion due to Raman energy transfer, Rayleigh backscattering, fibre loss, spontaneous emission noise and blackbody radiation noise are included.

Simulations are performed by numerically solving the above coupled differential equations using the Runge–Kutta method, with the boundary conditions $P_{\mathrm{sr}}(L)=P_{\mathrm{sf}}(L)\cdot R$ and $P_{\mathrm{pr}}(L)=P_{\mathrm{pf}}\cdot R$, where P_{sf}, P_{sr}, P_{pf}, P_{pr} are the power of the forward signals, the reflected backward signals, the forward pumps and the reflected backward pumps, respectively, R is the reflectivity of the reflector. In the simulations, SSMF was assumed as the gain fibre. The pump lasers at the wavelengths of 1426, 1440, 1454, 1472 and 1496nm were used. Forty signal channels covering 1530–1610nm with a launch power of 0.01mW were used. R was assumed as 93%.

The simulated power distribution of the pumps along fibre distance is shown in Fig.3. The simulated total power evolution along fibre length of each pump wavelength is shown in Fig.4. The total power is the sum of the forward- and backward-reflected pump power. The fibre was assumed as 10km SSMF and pump power was assumed as 200mW for each wavelength. Clearly, due to the pump-to-pump Raman interactions, the pump power at longer wavelength is higher at the fibre output end before being reflected, which means that more power is reflected for longer pump wavelength, resulting in the total power at longer pumping wavelength maintaining a higher level along fibre length than at shorter pumping wavelength (shown in Fig.4). Moreover, this increased efficiency depends on fibre length. With the fibre length increasing, it increases at first due to longer Raman gain medium length. However, because the power that can be reflected decreases due to fibre attenuation as

well, it begins to decrease after a certain fibre length.

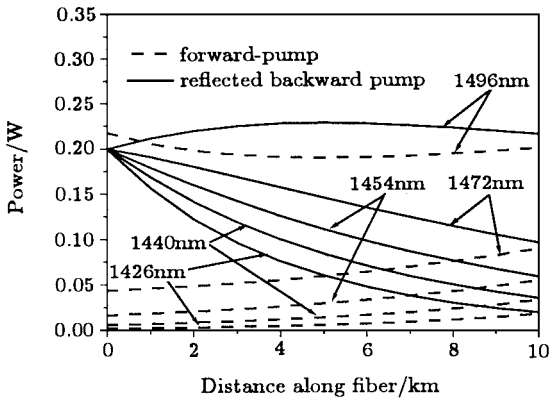


Fig.3. Pump power along fibre, including forward- and backward-reflected pump.

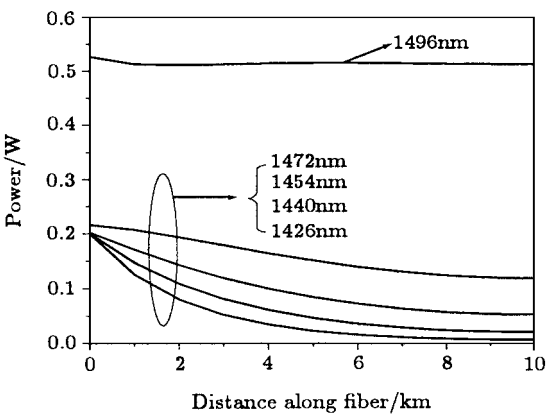


Fig.4. Total power evolutions of individual pump.

To see clearly the effect of reflecting signals on the increase in gain, we simulated the gain characteristic of a Raman amplifier, in which only signals are reflected and the pump only single-passed. Pump power was assumed as 437.7, 314.9, 285.0, 110.6 and 182.75mW at 1426, 1440, 1454, 1472 and 1496nm, respectively. Forty signal channels covering 1530–1610nm with a launch power of 0.01mW were used. Gain fibre was assumed as SSMF. Figure 5 shows the simulated signal power distributions along fibre. Since signals propagate through the gain medium for a second time, the gain is increased to nearly two times.

Finally, we simulated the gain of the four following schemes of Raman amplifiers for comparison: (a) typical co-pumped configuration in which both signals and pumps singly pass through the fibre in the same direction, (b) a signal single-pass and pump double-pass configuration, (c) signal double-pass and pumps single-pass configuration and (d) the signal double-pass and pump double-pass configuration as we have proposed. The result is given in Fig.6. In the simulation, pump power was assumed as 437.7, 314.9, 285.0, 110.6 and 182.75mW for the wavelengths of 1426, 1440, 1454, 1472 and 1496nm, respectively. Forty signal channels covering 1530–1610nm with a launch power of 0.01mW were used. Fiber was assumed as 10km SSMF. Clearly, by only reflecting the pumps, the gain is increased, especially in the *L*-band. By only reflecting the signals, the gain can be increased to a larger degree. When both signal reflection and pump reflection are introduced, the gain can be increased to a much higher overall level.

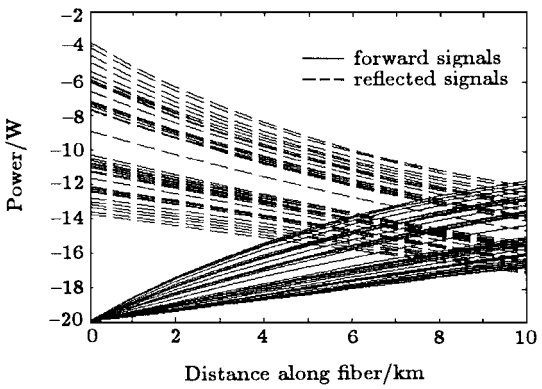


Fig.5. Signal power along fibre for double-pass Raman amplifier scheme.

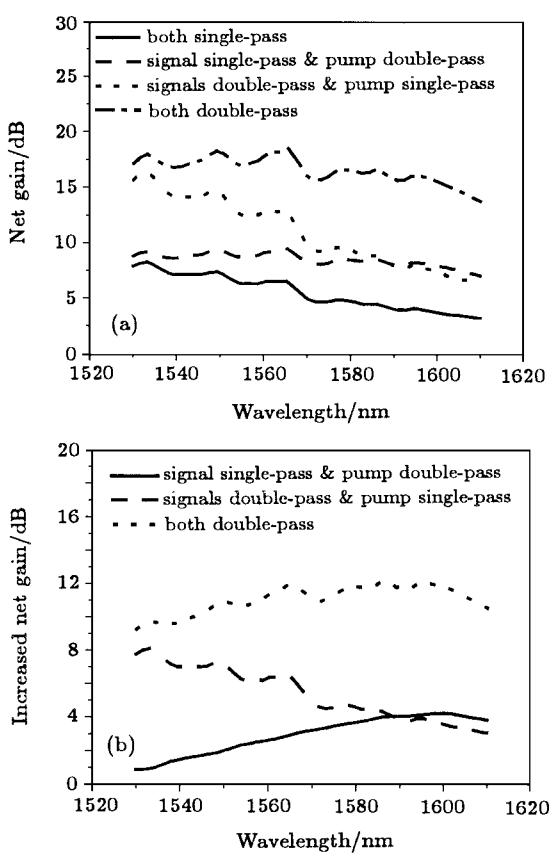


Fig.6. Simulated comparison result of net gain in the four Raman amplifier schemes. (a) Net gain, (b) increased net gain compared with that of a typical single-pass Raman amplifier.

3. Experimental results and discussion

The experimental configuration of the double-pass Raman amplifier with simultaneously reflecting signals and pumps is as shown in Fig.1. A broadband light emitting diode was used as the input signal source for the small signal gain measurement of the amplifier. The pump lasers at the wavelengths of 1426, 1440, 1454, 1472 and 1496nm were employed. A one-end gilt fibre was used as the broadband reflector that has a relatively high and flat reflectivity over a range more than 200nm. This kind of reflectivity cannot be easily achieved by using a FBG or a chirped FBG. Besides this, the cost of this reflector is much lower than that made of FBGs. Figure 7 shows the measured reflectivity spectrum covering the wavelength range of 1420–1620nm, in which the reflectivity varies smoothly from 93% to 98%. That is to say, in our experiments, about 93% pump power and signal power can be reflected. In our experiments, 10km SSMF was used as gain fibre. The pump power was set to 437.7, 314.9, 285.0, 110.6 and 182.75mW at the wavelengths of 1426, 1440nm, 1454, 1472 and 1496nm, respectively. A WDM operating at 1420–1500nm/1530–1610nm was used for coupling pumps and signals. The measured net gain is given in Fig.8., which is about 14dB.

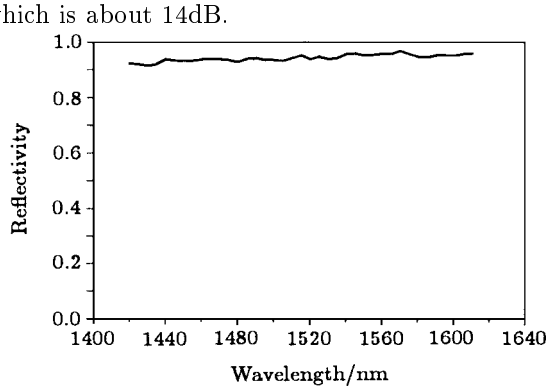


Fig.7. Reflectivity spectrum of the end gilt fibre.

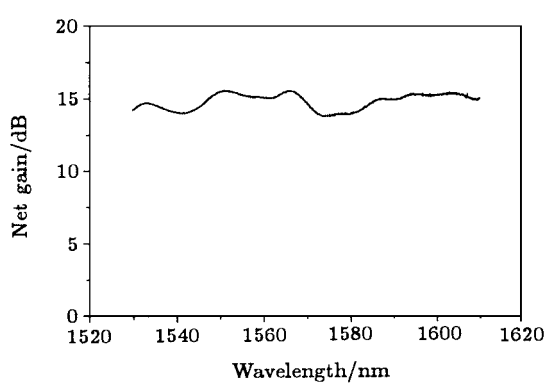


Fig.8. Measured net gain of the double-pass Raman amplifier.

To further show the advantage on gain efficiency of this simultaneous double-pass configuration, we then measured the net gain of other three Raman amplifier configurations as follows: (a) the typical co-pumped configuration, in which both the signals and pumps singly pass through the fibre in the same direction; (b) signal single-pass and pump double-pass configuration; (c) signal double-pass and pump single-pass configuration. The experimental setups of the above three configurations are shown in Figs.9(a)–(c), respectively. The comparison results are shown in Fig.10.

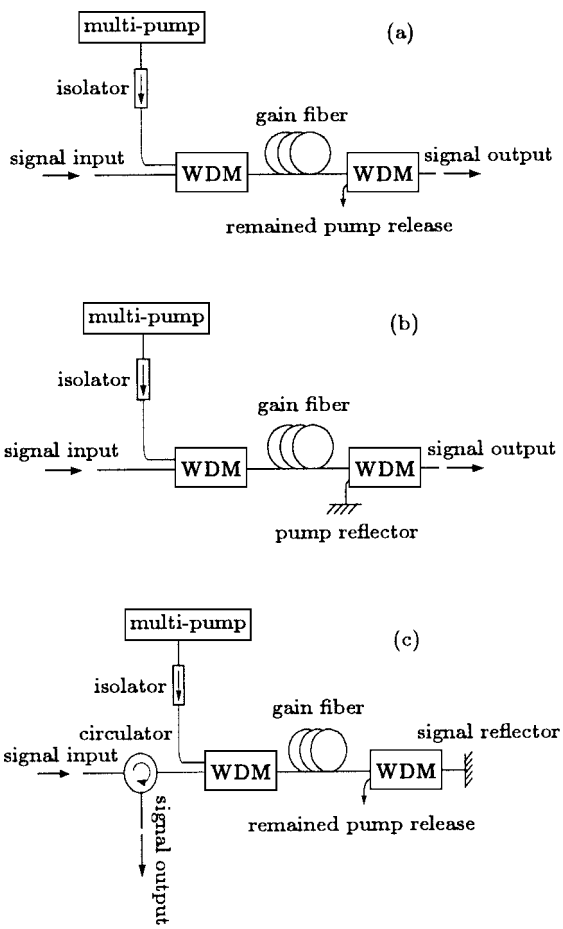


Fig.9. Experimental setups of Raman amplifiers for three types of configuration. (a) The typical co-pumped configuration. (b) Signal single-pass and pump double-pass configuration. (c) Signal double-pass and pump single-pass configuration.

In all the three reflection Raman amplifier configurations (Figs.1, 9(b) and 9(c)), Raman gain were increased compared with the typical co-pumped configuration. However, the configuration proposed by us (Fig.1) obviously has an advantage over the other two configurations. Here, the increased gain efficiency is

defined as the increased gain (dB) divided by the net gain of a typical co-pumped Raman amplifier. The increased gain efficiency increased from 4.4% to 88.2% in the wavelength range of 1530–1610nm for the configuration of signal single-pass and pump double-pass, while it increased from 43.5% to 77.5% for the configuration of signal double-pass and pump single-pass. For our configuration, the increased gain efficiency reached 99.5%–249.9%.

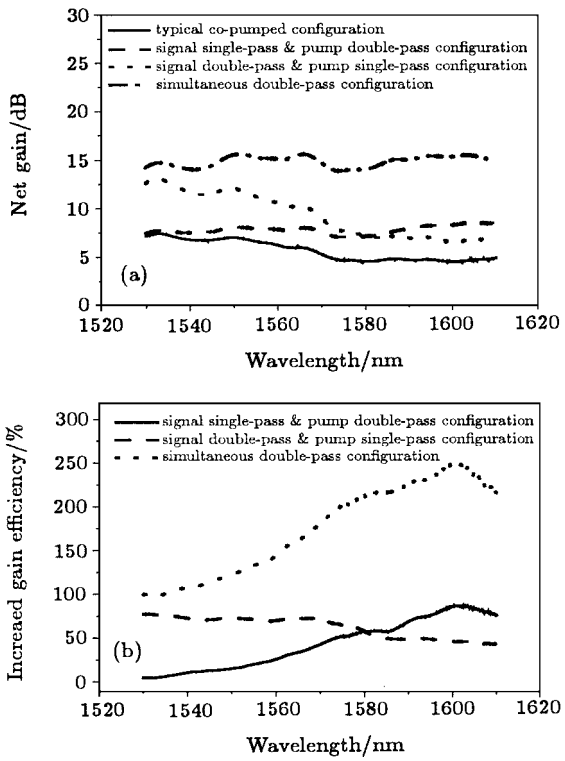


Fig.10. Experimental results of Raman amplifiers for four types of with the fibre length of 10km: (a) net gain (b) increased gain efficiency (%) in the three reflection configurations compared with co-pumped configuration.

Finally, we measured the net gain of the following two Raman amplifiers for comparison: (a) the typical co-pump Raman amplifier with 25km SSMF, (b) the simultaneous double-pass Raman amplifier with 10km SSMF. We keep the pump wavelength and power the same for the two amplifiers experiments, as 437.7, 314.9, 285.0, 110.6 and 182.75mW at the wavelengths of 1426, 1440, 1454, 1472 and 1496nm, respectively. The experimental results (shown in Fig.11) reveal that the net gain for the simultaneous double-pass RA with 10km SSMF is much higher than that for the co-pumped RA with 25km SSMF. This means that the proposed RA configuration can remarkably shorten the fibre and reduce the device size of the amplifier. This advantage is very important for a discrete optical fibre amplifier. The gain in this kind of Raman amplifier is quite stable as proved by repeated experiments. Besides, because pumps propagate through the gain fibre for a second time in the opposite direction of the input, which is similar to the bi-direction configuration, the noise figure (NF) in this proposed Raman amplifier is probably between the co-pumped Raman amplifier and the counter-pumped one with the same gain level. In other words, the OSNR in such a double-pass Raman amplifier is probably much higher than the typical co-pumped (or counter-pumped) Raman amplifier under the same pump condition.

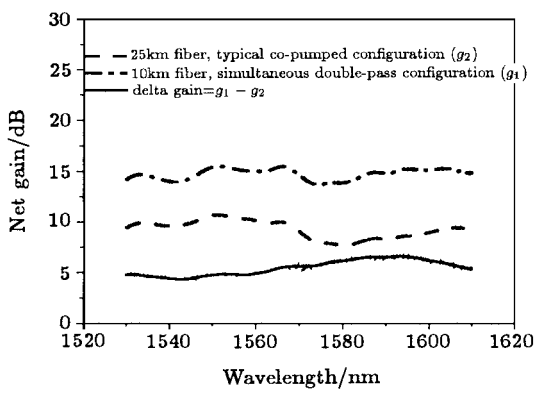


Fig.11. Measured net gain of two Raman amplifiers: (a) the typical co-pumped configuration, the fibre length is 25km; (b) the simultaneous double-pass configuration, the fibre length is 10km.

4. Conclusion

A wideband double-pass discrete Raman amplifier with simultaneous reflection of signals and multi-pump is proposed. The gain characteristic of the Raman amplifier was studied theoretically and experimentally together with that of three other Raman amplifier schemes for comparison. Because both signals and pumps are reflected to propagate the gain fibre a second time, gain efficiency can be increased remarkably. Compared with the other two reflection schemes with only reflecting pump or signal, this new scheme has an obvious advantage in enhancing the gain efficiency. It is also proved numerically and experimentally that the increased gain efficiency in the wideband double-pass discrete Raman amplifier is not symmetrical over the broadband due to the Raman interactions between multi-pumps. This kind of new configuration Raman amplifier can be easily realized by incorporating an end-gilt fibre in experiment. The experimental results are in agreement with the results of numerical simulation.

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