Wide-band double-pass discrete Raman amplifier with reflection of signals and pumps

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A wide-band (1530−1610 nm) and high efficient double-pass discrete Raman amplifier is reported. In this Raman amplifier, by using a one-end gilded fiber as the broadband reflector, signals and multi-pump are both reflected to propagate through the gain fiber for a second time. 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 proposed new configuration have been experimentally studied by comparing with the recently existing Raman amplifier configurations.

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Wide-band fiber amplifiers are indispensable to wide-band and long-distance dense wavelength division multiplexing (DWDM) systems[1,2]. Recently, discrete Raman amplifiers (RAs) have attracted significant attention to extend new gain bandwidth as S- or L-band due to the wavelength independence of Raman gain[3,4]. However, the low Raman conversion efficiency makes the amplifiers require high-power pump lasers and long gain fibers to achieve an enough gain, which results in a high cost. Therefore, it is important to enhance the gain efficiency of the discrete Raman amplifier.

Nicholson reported a Raman amplifier with pump reflectors, in which only pump was reflected[5]. Tang and Shum designed a double-pass discrete Raman amplifier based on fiber Bragg grating (FBG), in which only signal was reflected[6]. The expected increase in gain was achieved in both reflection schemes. However, in their experiments, only one pump wavelength or one signal wavelength was employed. Besides this, the range of the reflected wavelength was also limited by the stop bandwidth of the FBG reflectors.

In this letter, we propose a wide-band double-pass discrete Raman amplifier based on a one-end gilded fiber, which has a flat reflectivity of more than 93% over the wavelength range of 1420−1620 nm. In the wide-band double-pass configuration, both the pumps and the signals covering C + L-band are reflected (called as the double-pass configuration below). Compared with the configurations of only reflecting signals or pumps, the proposed double-pass configuration has an obvious advantage on gain efficiency, which is proved by the following experimental results.

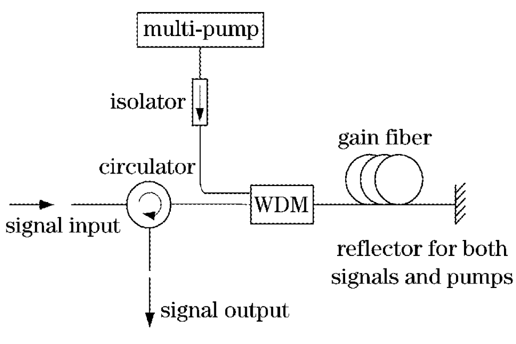

Fig. 1. Configuration of the proposed double-pass discrete Raman amplifier.

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

In this kind of Raman amplifier, pump was reflected to propagate through the gain fiber for a second time, which could increase pump efficiency because of more pump power in the gain fiber. On the other hand, the reflection of signals could also enhance gain due to the doubled gain medium length (or to say, the doubled fiber length). So, when the reflection of both signals and pump was introduced, the gain of the Raman amplifier could be increased to a much higher level with the same pump condition and the same fiber length.

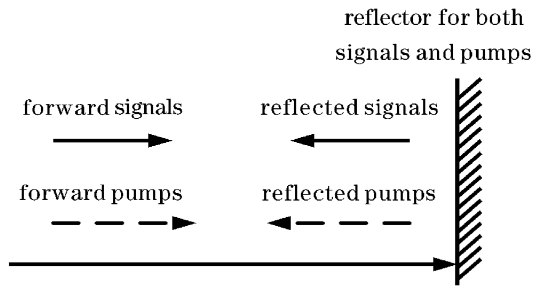

Fig. 2. The signals and the pumps in the Raman amplifier.

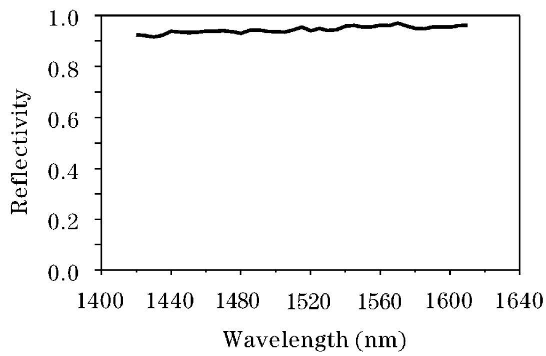

Fig. 3. Reflectivity spectrum of the one-end gilded fiber.

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 1496 nm were employed. A one-end gilded fiber was used as the broadband reflector that had a relatively high and flat reflectivity over more than 200 nm. 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 of FBG. Figure 3 shows the measured reflectivity spectrum covering the wavelength range of 1420−1620 nm, in which

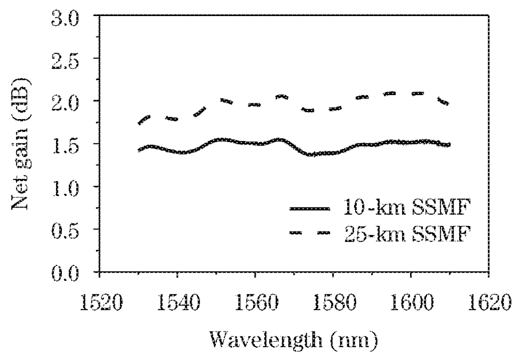

Fig. 4. The measured net gain of the double-pass Raman amplifier.

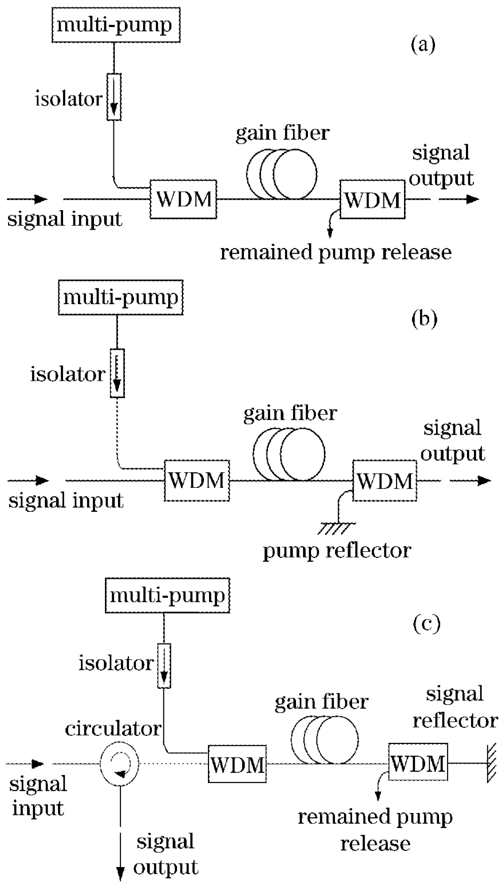

Fig. 5. Experimental setups of Raman amplifiers for three type of configurations. (a): The typical co-pumped configuration; (b): signals single-pass and pumps double-pass configuration; (c): signals double-pass and pumps single-pass configuration.

the reflectivity varies smoothly from 93% to 98%. That is to say, in our experiments, there was about 93% pump power and the signal power could be reflected. In our experiments, 10-km standard single mode fiber (SSMF) and 25-km SSMF were used as gain fiber, respectively. For 10-km SSMF, the pump powers were set to 437.7, 314.9, 285.0, 110.6, and 182.75 mW at the wavelengths of 1426, 1440, 1454, 1472, and 1496 nm, respectively. To achieve the same gain flatness, for 25-km SSMF, the pump powers were chosen as 437.7, 352.9, 275.0, 106.0, and 182.7 mW, respectively. The working wavelengths of the circular were from 1530 to 1610 nm. A wavelength division multiplexer (WDM) operating at 1420−1500 nm / 1530−1610 nm was used for coupling pumps and signals. The measured net gain is given in Fig. 4, which is about 14 dB for 10-km SSMF and 18 dB for 25-km SSMF, respectively.

To further show the advantage on gain efficiency of this 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 fiber in the same direction; b) signals single-pass and pumps double-pass configuration; c) signals double-pass and pumps single-pass configuration. The experimental setups of the above three configurations are shown in Figs. 5(a), (b), and (c), respectively. For each configuration, the situations for both 10-km SSMF and 25-km SSMF were experimentally studied with the same pump wavelength and pump power. The comparison results are shown in Figs. 6 and 7.

In all the three reflection Raman amplifier configurations (Fig. 1, Figs. 5(b) and (c)), Raman gain were all increased compared with the typical co-pumped

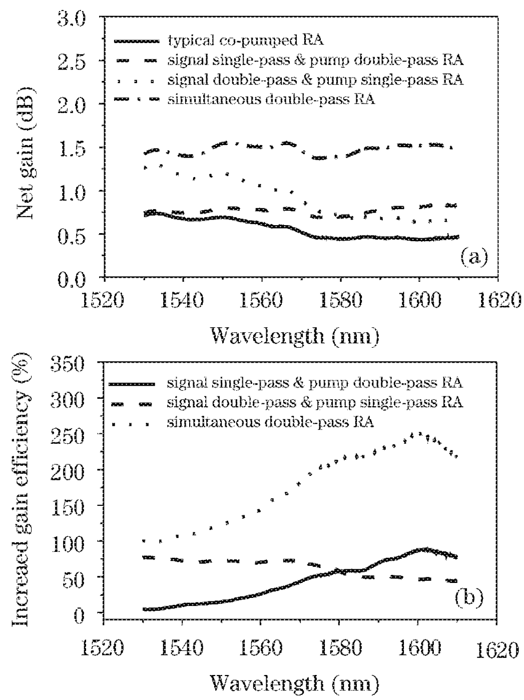

Fig. 6. (a): Net gain for four type Raman amplifiers with the fiber length of 10-km; (b): increased gain efficiency in the three reflection configurations compared with co-pumped configuration.

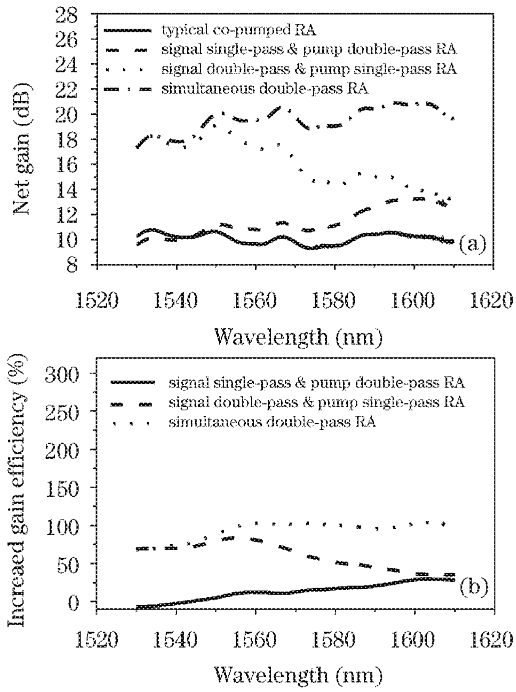

Fig. 7. (a): Net gain for four type Raman amplifiers with the fiber length of 25 km; (b): increased gain efficiency in the three reflection configurations compared with co-pumped configuration.

configuration. However, the proposed configuration (Fig. 1) obviously has an advantage over the other two configurations. Here, we defined the value of increased Raman gain divided by the Raman gain of a typical co-pumped Raman amplifier as the increased gain efficiency. When 10-km SSMF was used as gain fiber, the increased gain efficiency was from 4.4% to 88.2% in the wavelength range of 1530−1610 nm for the configuration of signals single-pass and pumps double-pass, while it increased from 43.5% to 77.5% for the configuration of signals double-pass and pumps single-pass. And for our configuration, the increased gain efficiency reached at 99.5%−249.9%. However, the increased gain efficiency is related to fiber length. With the fiber length growing, the increased gain efficiency falls due to the decrease of the reflected pump power caused by fiber attenuation. As shown in Fig. 7(b), the increased gain efficiency is 67%−104% for 25-km SSMF.

An interesting fact is that, when 25-km SSMF was used, the increased gain efficiency in the signals single-pass and pumps double-pass configuration is negative in the range of 1530.0−1543.5 nm (see Fig. 7(b)). The reason is that when pumps are reflected, the effect of pump-to-pump Raman interaction[7] is enhanced, which means the pumps at shorter wavelengths transfer more power than those at longer wavelengths. This phenomenon gets more serious with the increase of the fiber length.

At last, we measured the net gain of the following two Raman amplifiers for comparison: a) the typical co-pump Raman amplifier with 25-km SSMF, b) the double-pass Raman amplifier with 10-km SSMF. We keep the pump wavelength and power same for the two amplifiers experiments, as 437.7, 314.9, 285.0, 110.6, and

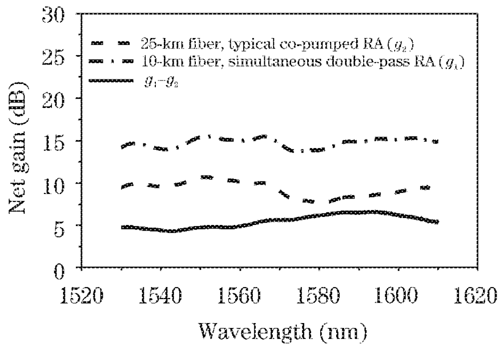

Fig. 8. Measured net gain of two Raman amplifiers.

182.75 mW at the wavelength of 1426, 1440, 1454, 1472, and 1496 nm, respectively. The experimental results (see Fig. 8) reveal that the net gain for the double-pass Raman amplifier with 10-km SSMF is much higher than that for the co-pumped Raman amplifier with 25-km SSMF. It means that the proposed Raman amplifier configuration can remarkably save fiber and reduce the device size of the amplifier, which is very important for the discrete optical fiber amplifier.

To our knowledge, a wide-band (80 nm) double-pass discrete Raman amplifier with reflection of both the signals and the multi-pump was first reported. It has been successfully proved by the experiments that the gain efficiency is increased remarkably in the double-pass Raman amplifier compared with the typical co-pumped configuration for the same pump power and fiber length.

This proposed Raman amplifier configuration is more efficient to enhance the gain than the configurations of only reflecting signals or pumps do. For the proposed configuration, the total pump powers can be decreased or the fiber length can be cut down for the same net gain compared with the typical co-pumped Raman amplifier. This kind of new Raman amplifier configuration can be easily formed by using an end-gilded fiber. These advantages are very valuable for the discrete Raman amplifier.

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