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Improvement of Raman Amplifier Gain Flatness by Broadband Pumping Sources

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Abstract—We propose the design of 100-km flat-gain backward-pumped Raman amplifier with four broad-linewidth 14XX-nm pumps with less than 0.2-dB gain-ripple in 1528–1584 nm bandwidth. We have found this pump scheme as a very efficient approximation for continuous pump spectrum with the similar Raman gain flatness parameters. Also, we present investigations of pump instability impact on resulting Raman gain flatness.

The fiber Raman optical amplifier is quickly emerging as an important part of long-distance, high-capacity, and high-speed optical communication systems [1]. The decreasing cost of high-power semiconductor lasers and the increasing need in optical fiber transmission for more gain bandwidth, lower gain-ripple, and lower noise figures make Raman amplifiers a more attractive technology than the traditional erbium-doped fiber amplifier.

The nature of the Raman effect in conventional silica-glass fibers results in the fact that the peak of the relatively broad gain contour of stimulated Raman scattering depends only on the pump wavelength, not on the fiber dopant. In connection with this, the Raman amplifier can be used for the design of an arbitrary gain contour by combining several pump sources. By a proper choice of the pump powers and wavelengths it is possible to reduce the gain-ripple of the corresponding Raman gain contour in a broad wavelength range.

Flattening of the gain contour in wideband Raman amplifiers is one of the most important tasks for the designers of Raman amplifiers. Currently, different pump techniques are being used for Raman gain flattening. The most traditional of them is “WDM pumping,” which employs a set of several 14XX-nm diode laser pumps with optimized wavelengths and/or output power. The best gain flatness of Raman amplification in the C- plus L-band that has been achieved with this technique (the pump count being ~10) is on the order of 0.1 dB [2], depending on the average gain level. Such pumping schemes for fiber Raman amplifiers cannot be considered optimal, due to the relatively high cost and complexity of the overall amplification system. In addition, each diode laser may require thermostable packaging in order to prevent power and wavelength fluctuations in the output radiation that would compromise the final Raman gain contour flatness.

At present, several methods for the simplification (reduction of the pump source count) of the pump scheme exist, which allow the output parameters of the Raman amplification spectrum to be maintained intact in a wide spectral range. An alternative to “WDM pumping” could be either spectrally broadened pump sources [3, 4] or a single pump source that is fast-tunable in a wide wavelength range (“SMART” Raman pumping) [5]. Note, however, that this pump scheme has not yet been realized.

The theoretical prediction of Raman gain contour and Raman amplifier pump spectrum optimization are now major tasks for Raman amplifier designers. The best approach to the optimization may turn out to be a solution of the inverse Raman scattering problem, i.e., finding a specific continuous spectrum of the pump source that would ensure minimal ripple of the Raman gain contour and optimization of other parameters of the amplifier. This approach to the optimization of Raman amplifiers has allowed us to theoretically predict the nonuniformity of a Raman amplification contour less than 0.0025 dB within the amplification range of 1530–1595 nm [6].

The interaction between the spectral components of the signal and the pump radiation is defined by a system of nonlinear differential equations with boundary conditions at the ends of the fiber. Because of this, an analytical solution of the inverse Raman scattering problem is impossible, so that numerical methods must be used for calculation of the Raman amplification contour.

The primary complication in calculations of the contour of a Raman amplifier with a multiwavelength pump is the Raman interaction between the spectral components of the pump system, which leads to energy transfer from short wavelengths of the pump spectrum to longer wavelengths. Time-division multiplexing (TDM) of the pump spectral components [5] can be used to avoid this type of interaction. Without TDM of the different pump sources, it is necessary to account for all the interactions among the various pump and signal wavelengths. It is most essential in the case of a continuous pump radiation spectrum.

In this work we made an attempt to solve the problem of optimal Raman amplifier pump spectrum

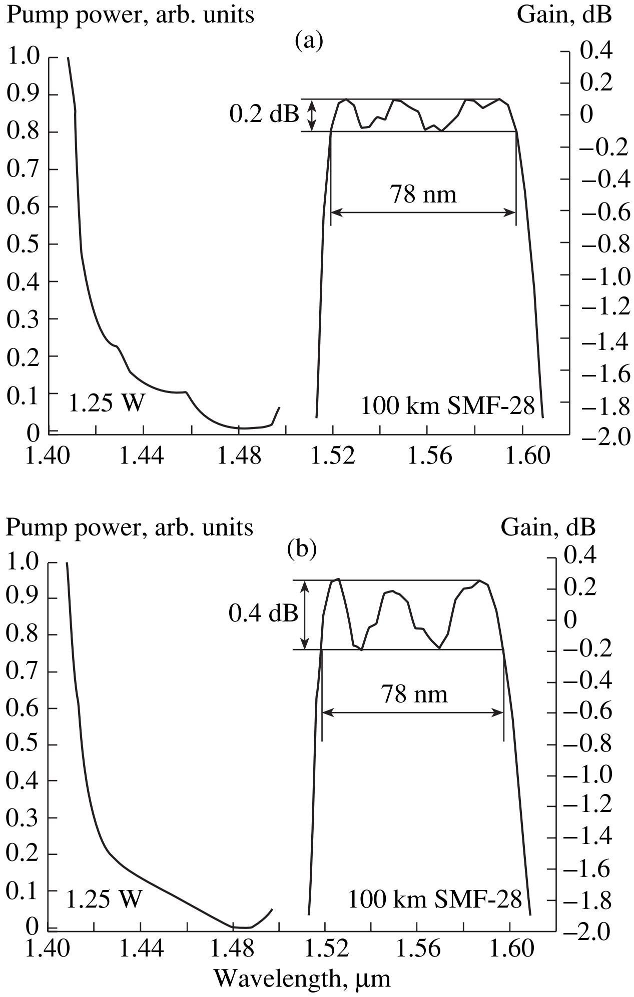

Fig. 1. Continuous spectrum of pump radiation (a) and its polynomial approximation (b) with the corresponding spectra of Raman amplification for a 100-km fiber Raman amplifier based on SMF-28.

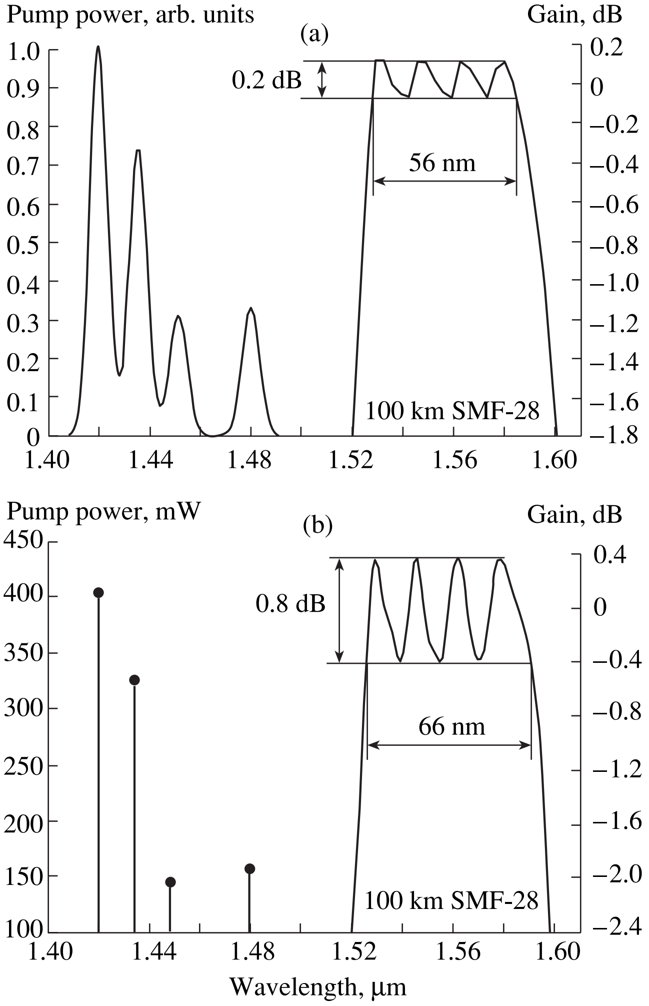

Fig. 2. Optimal four-pump spectra and corresponding Raman gain contours for a 100-km backward-pumped Raman amplifier in the case of broadened (a) and monochromatic (b) pumps.

directly, by varying and/or optimizing the contour of a continuous pump spectrum using a full numerical model of Raman scattering [7]. The results of Raman gain flattening for 100-km SMF-28 with 1.25 W overall pump power are shown in Fig. 1.

Raman gain flatness in this case was less than 0.2 dB for the 1520–1598-nm range (Fig. 1a). The small-signal (–10 dBm/channel) average gain was 0 dB, which is related to optical signal recovery at the end of the transmission line. It is important to note that the numerical results of calculations for Raman gain flatness could be improved even in the frame of the current numerical model by a reduction of the frequency step-size in the simulation of Raman gain, but this would lead to a considerable increase in the calculation time. In spite of larger Raman gain ripple as compared with [6], our case differs from the latter in that it has a substantially simpler form and may not require a complicated pump scheme for the realization of this pump spectrum. In addition to the solution of the continuous pumping of a Raman amplifier, we presented a polynomial approximation (seventh power) of a continuous pump spectrum and the corresponding Raman gain contour (Fig. 2b) with less than 0.4 dB Raman gain-ripple in the same spectral band. This approach can be of service in cases in which it is necessary to represent the pump radiation spectrum by an analytical function.

The experimental implementation of the proposed pump spectrum is an important issue in the modeling of Raman amplifiers. In the case of a continuous spectrum of the pump radiation, it is possible to shape such a spectrum either directly with supercontinuum generation sources or with a number of broad-line pump sources that would overlap into the necessary continuous pump spectrum.

Considering the continuous pump spectrum of a Raman amplifier (Fig. 1a), one clearly sees that it has approximately four main maxima around 1409, 1428,

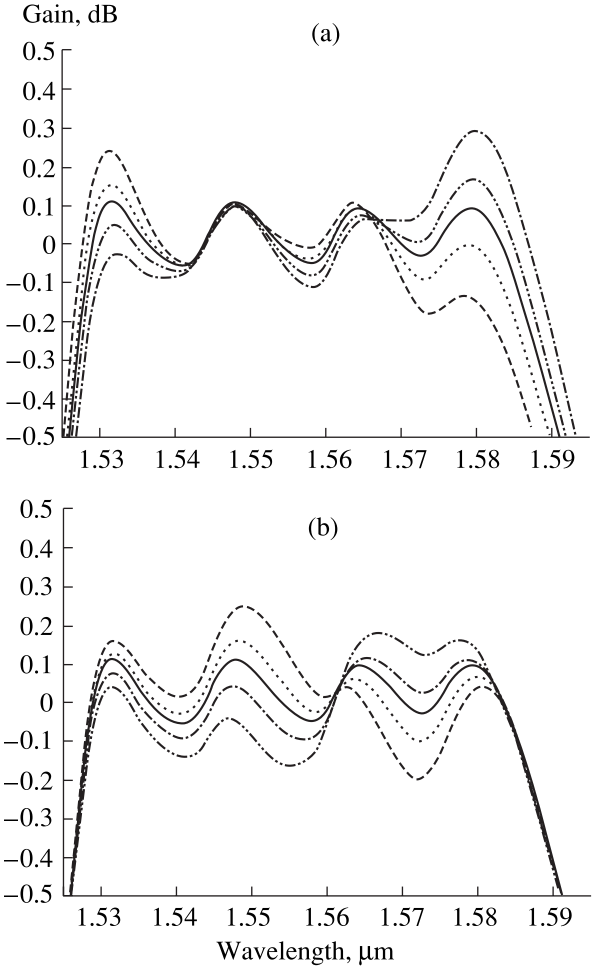

Fig. 3. Raman gain contours for pump-power (a) and wavelength (b) deviations from their optimal values in a backward-pumped 100-km SMF-28 Raman amplifier.

1458, and 1497 nm. The main idea was to form a continuous pump spectrum, which would be close to the optimal one that is shown in Fig. 1, by combining four Gaussian-shaped pump sources with sufficiently wide spectra to form a continuous spectrum. The consideration of the suggested technique is justified from the viewpoint of the experimental implementation of a Raman amplifier based on this approach. The requisite spectral broadening can be achieved in conventional diode lasers without special stabilization systems and without any narrowing of the generation spectrum. In such a case, the line width of such a laser may reach 10–15 nm, and the combination of four diode lasers with corresponding output wavelengths will be sufficient to cover the necessary wavelength range. Besides that, the necessary spectral broadening of the pump radiation may be obtained with the help of nonlinear interactions both in special fibers [3, 4] and in conventional communication fibers [4].

In connection with this, we have numerically studied a Raman amplifier pump scheme in which four broad-linewidth pump sources form a combined spectrum that approximates the calculated optimal continuous spectrum of the pump with a total pump power of 1 W. The spectral lines of the pumps had 10-nm-wide Gaussian-broadened contours. The number of approximating pump sources was chosen from the point of view of the minimal overall cost of such a pump scheme, along with a sufficient coincidence of the superposition of the pump spectral contours with the optimal continuous pump spectrum, which allows us to achieve a relatively high gain flatness of the resulting Raman amplifier.

Results of the Raman amplifier gain contour optimization with four broad-linewidth pump sources are presented in Fig. 2a.

Shown in Fig. 2 are the resulting optimal spectral profiles of broad-linewidth (Fig. 2a) and monochromatic (Fig. 2b) four-pump and corresponding Raman gain contours for a 100-km backward-pumped Raman amplifier. The corresponding Raman gain ripple was less than 0.2 dB in the 1528–1584-nm bandwidth at the small-signal average gain of 0 dB in the case of broadened pump sources. The central wavelengths of the pump sources were as follows: 1420, 1435.5, 1451.3, and 1480 nm. In comparison with this situation, while using monochromatic pump sources with the same wavelengths it is only possible to achieve 0.8 dB Raman gain flatness in the band, which demonstrates the efficiency of using broadened pumps for Raman gain flattening.

Thus, we have numerically demonstrated that relatively high Raman gain flatness (<0.2 dB) is also achievable in fiber Raman amplifiers with four broadband (~10 nm) pump sources. Obviously, by using more pump sources for Raman gain flattening, better results of gain-ripple minimization can be obtained. But, on the other hand, the reduction of the number of Raman amplifier pump sources can be efficient from the viewpoint of the overall cost of such a pump scheme, and it can be very important for the minimization of the impact of any possible instability of the pump sources on the resulting Raman gain contour.

In relation to this, a numerical investigation of the impact that the power and generation wavelength instabilities of the pump sources may have had has been conducted for a four-broadband-source pumping scheme with a 100-km Raman amplifier. We have studied different pump schemes in which either the pump-source powers differed from the optimal values by ±2–5%, or the pump wavelengths were shifted from the optimal values by ±0.5 nm. We consider these values of pump and wavelength deviation to be realistic for conventional diode lasers without any stabilization systems.

In Fig. 3a and 3b, we have presented the Raman gain contours for different types of pump-source power and wavelength deviation. The optimal situation, without any pump deviations, is shown by the solid line in

Fig. 3a. Also, Fig. 3a demonstrates situations in which the deviations of the pump sources were the following: +5%, –5%, +5%, –5% (dashed line); +2%, –2%, +2%, –2% (dotted line); –2%, +2%, –2%, +2% (dash-dot-dot line); and –5%, +5%, –5%, +5% (dash-dot line). The Raman gain flatness for these situations was 0.55, 0.32, 0.28, and 0.52 dB, correspondingly, within the 1528–1584-nm wavelength range (in comparison to the optimal situation, which has 0.2 dB Raman gain flatness).

The Raman gain contours for different cases of two central pump source wavelength (1440 and 1460 nm) deviations are given in Fig. 3b: +0.5, –0.5 nm (dashed line); +0.2, –0.2 nm (dotted line); –0.2, +0.2 nm (dashed line); –0.5, +0.5 nm (dotted line). In these cases, the gain flatness of the corresponding Raman amplifier was 0.45, 0.25, 0.22, and 0.32 dB within the 1528–1584-nm wavelength range. The explored combinations of fluctuations in the wavelength and power of the pump sources naturally do not encompass all possible deviations in the pump radiation parameters from their optimal values. In any case, the stability of pump radiation parameters must be somehow controlled in order to achieve a spectrally uniform Raman gain. The results given here are based on typically possible fluctuations of the pump radiation parameters; as can be seen from the modeling results, these types of fluctuations do not lead to critical deformation of the Raman gain contour.

In conclusion, we have presented results from the numerical study of methods for finding the optimal spectral distribution of pump radiation for the best uniformity of the Raman gain contour within the C + L communication band, as well as the possibility of approximating the calculated optimal pump radiation spectrum with only four broad-line pump sources. Both conventional diode lasers without wavelength selection elements and narrow-band CW sources with nonlinear broadening of their generation lines can be used in the proposed technique. For a continuously backward-pumped 100-km Raman amplifier based on SMF-28, with a 1.25 W overall pump power, we have found the optimal shape of the pump spectrum, which resulted in a 0.2 dB Raman gain flatness in a 78-nm band (1520–1598 nm) with a 0-dB small-signal average gain. For an approximation of the determined continuous pump spectrum, we searched for an optimal composition of four broadband pump sources, the resulting combination of which ensured a 0.2-dB Raman gain flatness in a 56-nm band (1528–1584 nm) with a 1 W overall pump power and a 0-dB small-signal average gain.

Apart from the above, the influence of instabilities in the power and wavelength of pump sources with spectrally broadened generation lines on the resulting optimal Raman gain contour has been studied. It has been shown that power fluctuations on the order of ±2–5% and wavelength fluctuations on the order of ±0.2–0.5 nm lead to increased ripple within the Raman gain contour up to a level of ~0.5 dB.

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