Quantum Electronics **34** (6) 575 – 578 (2004)

OPTICAL FIBRES AND FIBRE LASERS

PACS numbers: 42.65.Dr; 42.81.Wg
DOI: 10.1070/QE2004v034n06ABEH002776

Fibre Raman amplifier pumped by continuous-spectrum radiation

S.M. Kobtsev, A.A. Pustovskikh

Abstract. **The results of numerical calculations of a fibre Raman amplifier pumped by continuous-spectrum radiation are presented. It is shown that the Raman gain flatness better than 0.1 dB can be achieved in the spectral region between 1528 and 1599 nm at the average gain of 7.7 dB, and the gain flatness of 0.042 dB in the case of the zero average small-signal gain in a 25-km SMF-28 fibre pumped by the 1-W and 364-mW backward radiation, respectively. Different variants of the approximation of the found optimal pump spectrum by a combination of four discrete radiation sources with broadened spectral lines are studied.**

Keywords: *stimulated Raman scattering, fibre Raman amplifier.*

1. Introduction

Fibre amplifiers based on stimulated Raman scattering are of great interest for fibreoptic communication systems [1]. Their advantages over semiconductor amplifiers and erbium-doped fibre amplifiers are the principal possibility to amplify a signal at any wavelength and the use of the fibre itself as a gain medium. In addition, they have a rather high signal-to-noise ratio and also can provide the broadening of the gain band upon pumping at different wavelengths [2]. The broadening of the gain band of amplifiers in modern fibreoptic communication systems is extremely urgent due to progress in the WDM technology and the development of new fibres with low optical losses in a broader spectral region (for example, Lucent AllWave or Corning TrueWave optical fibres).

In broadening the gain band of amplifiers, the primary problem is to provide the Raman gain flatness over the entire gain band, which is achieved conventionally by increasing the number (up to 12 [2] and above) of narrow-band pump sources emitting at different wavelengths and the adjustment of their wavelengths and output powers. The optimisation of the pump wavelengths and powers allows one to decrease the number of pump sources without any substantial deterioration of the basic parameters of Raman amplifiers [3]. This is also possible by using pump sources with broadened emission lines [4].

Another approach providing a high flatness of the Raman gain in broadband Raman amplifiers is based on the use of one pump source with a wavelength rapidly tunable in a broad spectral region [5]. However, this method was not experimentally realised so far.

The methods of multiwave and broadband pumping of Raman amplifiers were further developed by using a pump source with a continuous spectrum [6, 7], which can provide the best Raman gain flatness. The author of paper [6], using some approximations, solved numerically the inverse problem of a search for the pump band shape providing the maximum possible flatness of the Raman gain in the given spectral region. It was predicted theoretically that the Raman gain flatness can be better than 0.0025 dB within the band of width 65 nm when the width of the continuous pump spectrum is 85 nm. However, the pump spectrum considered in Ref. [6] has a relatively complicated structure, and it is quite difficult to use this pump scheme in real amplifiers. Therefore, it is interesting to attempt to find a simpler shape of a continuous pump spectrum that would provide the maximum possible flatness of the Raman gain band in the given spectral region.

2. Numerical model and results of the study

The propagation of a signal and the Raman interaction of the spectral components of the signal and pump radiation are described by a system of nonlinear equations. Therefore, the analytic solution of the inverse problem of Raman scattering in realistic models is impossible. For this reason, all the attempts to solve the inverse problem were based so far either on approximate models of the Raman gain in fibres, in which various quantities were averaged at certain calculation stages [6], or on a search for a certain algorithm for selecting the optimal continuous pump spectrum for a Raman amplifier [3, 7, 8].

Apart from the gain profile flatness, the average gain also plays an important role. If in the case of a distributed gain, it is necessary to reconstruct the initial power level of a signal radiation at the end of the communication line, then the efficiency of point amplifiers (or pre-amplifiers) determines the average value of the gain. It is obvious that the latter depends on the pump power; however, this dependence is nonlinear because of the Raman interaction between the spectral components of the pump radiation. Therefore, to determine the optimal pump spectrum for different parameters of a Raman amplifier, it is necessary to consider separately each specified amplification level.

S.M. Kobtsev, A.A. Pustovskikh Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; e-mail: pustovs@lab.nsu.ru

Received 23 October 2003; revision received 25 February 2004
Kvantovaya Elektronika **34** (6) 575 – 578 (2004)
Translated by M.N. Sapozhnikov

In this paper, we simulated a Raman amplifier using the most comprehensive numerical model [9], which takes into account basic physical processes affecting the Raman gain such as stimulated and spontaneous Raman scattering, Rayleigh scattering, temperature dependence, nonlinear interactions of the spectral components of the signal and pump, and cross (signal-pump) interactions in both directions, and the generation of high-order Stokes components:

$$\frac{\mathrm{d}P_\nu^{\pm}}{\mathrm{d}z} = \pm\Bigg\{ -\alpha_\nu P_\nu^{\pm} + \varepsilon_\nu P_\nu^{\mp} + P_\nu^{\pm}\Bigg[\sum_{\mu>\nu}\frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^{\pm}+P_\mu^{\mp}\right)$$

$$-\sum_{\mu<\nu}\frac{\nu}{\mu}\frac{g_{\nu\mu}}{A_\mu}\left(P_\mu^{\pm}+P_\mu^{\mp}\right) - 4h\nu\sum_{\mu<\nu}\frac{g_{\mu\nu}}{A_\mu}$$

$$\times\left\{1+\left[\exp\left(\frac{h(\nu-\mu)}{kT}\right)-1\right]^{-1}\right\}\Delta\mu\Bigg] + 2h\nu\Delta\nu$$

$$\times\sum_{\mu>\nu}\frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^{\pm}+P_\mu^{\mp}\right)\left\{1+\left[\exp\left(\frac{h(\mu-\nu)}{kT}\right)-1\right]^{-1}\right\}\Bigg\},$$

where $P_\nu^{\pm}$ is the spectral power in the interval $\Delta\nu$ at the frequency ν propagating in both directions; α_ν and ε_ν are the spectrally dependent coefficients of optical losses and Raman scattering in the fibre; $g_{\mu\nu}$ is the Raman gain of the signal at the frequency ν by pumping at the frequency μ; A_μ is the effective scattering area at the frequency μ; coefficients 2 and 4 appear in terms of spontaneous Raman scattering due to the depolarised noise spectral components in the cross signal – noise and noise – noise interactions; and h, k, and T are the Planck constant, the Boltzmann constant, and temperature, respectively. Figure 1 shows the spectral dependences of the optical loss coefficient α and the effective scattering area A_{eff} for a SMF-28 fibre, which were used in the numerical simulation of the Raman gain. The system of equations was supplemented by the boundary conditions at both ends of the fibre.

The optimal continuous pump spectrum for the Raman amplifier providing the maximum gain profile flatness was found by varying the spectral profile of the pump radiation. Calculations were performed for a standard 25-km SMF-28 fibre. The initial signal power coupled to the fibre was −10 dBm per channel and the total pump power was 1 W. The continuous pump spectrum was simulated wit the help of 31 monochromatic sources emitting spectral lines separated by 14 cm^{-1} in the 1408 – 1490-nm region. Figure 2 shows the optimal Raman gain profiles with the corresponding continuous pump spectra for the cases of nonzero and zero average gains. In the first case, the Raman gain flatness is less than 0.1 dB, while in the second case, it is 0.042 dB (the total pump power was 1 and 0.365 W, respectively). The spectral width of the gain profile was 71 nm in the range from 1528 to 1599 nm.

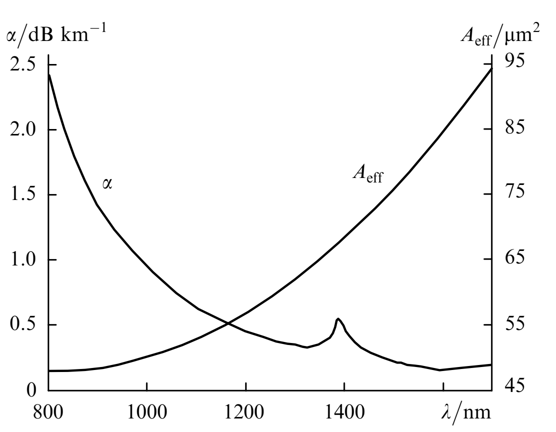


Figure 1. Spectral dependences of α and A_{eff} for a SMF-28 fibre.

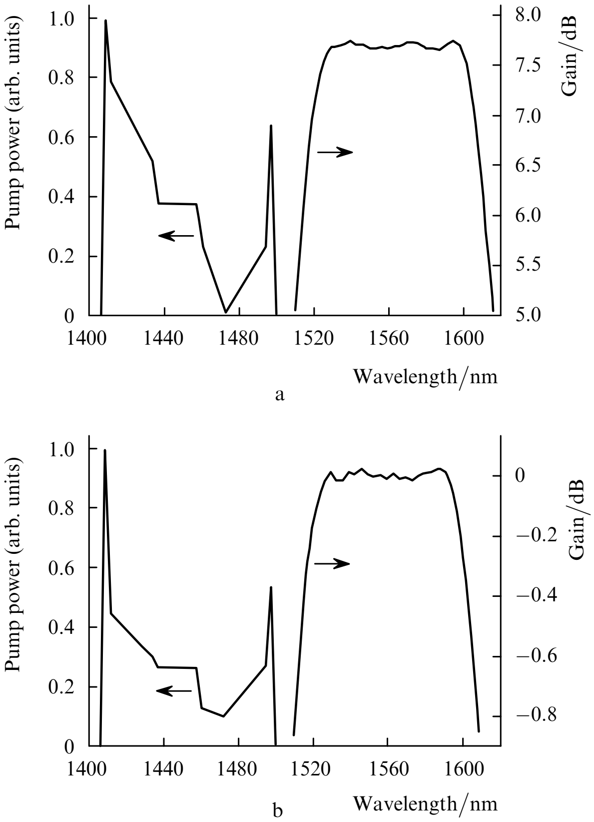


Figure 2. Optimal Raman gain profiles with the corresponding continuous pump spectra in the cases of nonzero (a) and zero (b) average gains.

The required shapes of optimal continuous pump spectra were obtained at the first stage of the optimisation. The shapes of these spectra were then approximated by a polynomial of seven degree (Fig. 3), the smoother approximated pump spectrum providing the same (0.1 dB) flatness in the same spectral region from 1528 to 1599 nm.

Because the shape of the optimal continuous pump spectrum (Fig. 3) is substantially simpler than that of the spectrum presented in Ref. [6], the former spectrum can be quite easily realised experimentally by slightly decreasing the number of broadband pump sources.

Note that the consideration of a set of broadband pump sources needed for producing a continuous spectrum is justified from the point of view of the experimental realisation of such a pump scheme. The required spectral broadening of the emission lines of available 14XX-nm sources can be achieved by using both special fibres [4] and diode lasers themselves without spectrally selective elements

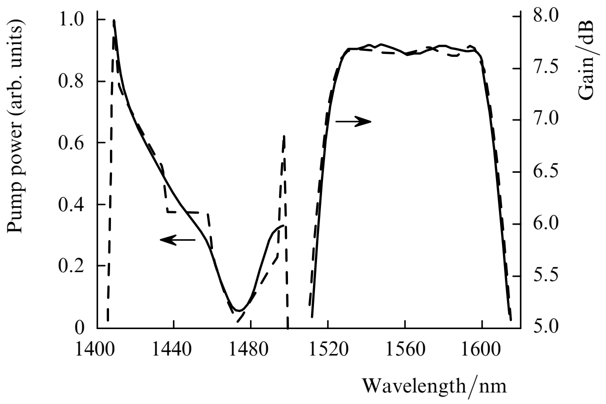


Figure 3. Raman gain profile for the discrete pump spectrum (dashed curve) and its polynomial approximation (solid curve).

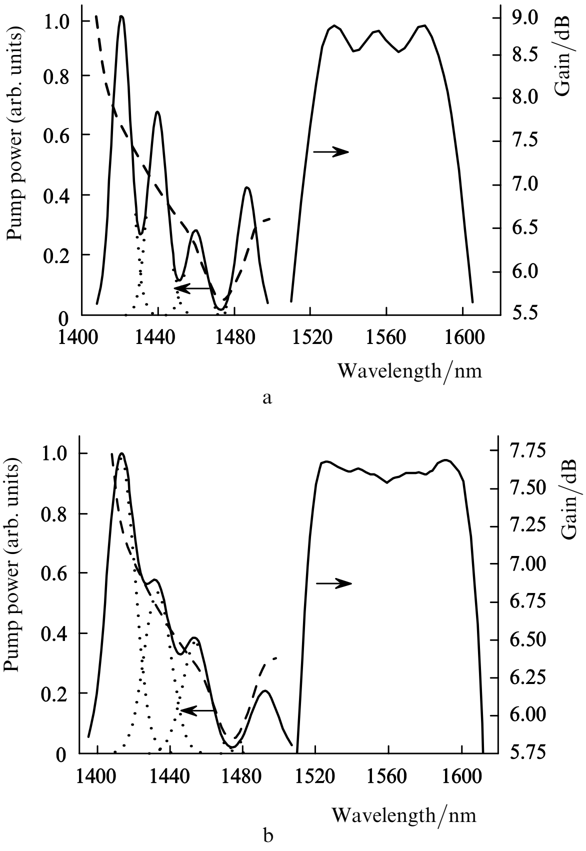
(narrowband mirrors, Bragg gratings, etc.). The emission linewidths of the 14XX-nm diode lasers without these elements can achieve 10 – 15 nm [10].

In this connection, we analysed numerically the pump scheme for a 25-km Raman amplifier, in which four broadband pump sources produce the spectrum approximating the found optimal continuous pump spectrum. The pump lines were described by Gaussians with the FWHM 10 and 15 nm and the wavelengths and powers of the pump lines were optimised to obtain the best fit of the optimal pump spectrum with the best Raman gain flatness.

Figure 4 shows the 1-W pump spectra consisting of four Gaussians and the corresponding Raman gain spectra. The Raman gain flatness does not exceed 0.3 dB in the spectral range from 1526 to 1578 nm for the average small-signal gain equal to 8.7 dB and the width of Gaussians forming the pump spectrum equal to 10 nm. The wavelengths of the pump sources were 1421, 1440, 1460, and 1487 nm. When the width of Gaussians was 15 nm, the Raman gain flatness did not exceed 0.15 dB in the spectral range from 1520 to 1600 nm for the average small-signal gain equal to 7.5 dB (the pump spectrum was formed by pump sources with wavelengths 1413, 1433, 1454, and 1492 nm).

It is important to note that one of the optimisation conditions in the simulation of the continuous pump spectrum of a Raman amplifier was a complete use of the pump spectrum power to form the Raman gain profile without spectral filtration. This condition is explained by the requirement of the maximum simplicity and efficiency of the pump scheme. The short-wavelength boundary of the pump spectrum was limited by the ~ 1400-nm absorption peak of a standard single-mode fibre, so that the Raman amplification with pump wavelengths shorter than 1400 nm is inefficient. However, the spectral range of amplification can be extended to the short-wavelength region by using fibres with lower optical losses (for example, Lucent AllWave or Corning TrueWave fibres).

From the point of view of the experimental realisation of a continuous pump spectrum for a Raman amplifier, this pump scheme seems most convenient. It can be optimally realised by using four laser diodes (without spectrally selective elements) emitting at the appropriate wavelengths or emitting lines broadened up to 10 – 15 nm.



a

b

Figure 4. Optimal pump spectra (dotted curves), their approximations (dashed curves), and the corresponding Raman gain profiles (solid curves) for the width of Gaussian components of the pump spectra equal to 10 (a) and 15 nm (b).

3. Conclusions

The shapes of continuous pump spectra for Raman amplifiers have been determined which provide the best Raman gain flatness in a broad spectral region. It is shown that the Raman gain flatness can be less than 0.1 dB in the case of the nonzero average small-signal gain and can be 0.042 dB in the case of the zero small-signal gain (the total pump power is 1 and 0.365 W, respectively). In this case, the spectral width of the gain profile is 71 nm. The variants of realisation of optimal continuous pump spectra using four pump sources with broadened emission lines have been considered. For pump linewidths of 15 nm, the Raman gain flatness does not exceed 0.15 dB in the wavelength range from 1520 to 1600 nm for the average small-signal gain eqal to 7.5 dB.

References

1. Dianov E. *J. Light Wave Tech.*, **20**, 1457 (2002).
2. Namiki S., Emory Y. *Sel. Top. Quantum Electron.*, **7**, 3 (2001).
3. Perlin V., Winful H. *J. Light Wave Tech.*, **20**, 250 (2002).
4. Ellingham T., Gleeson L., Doran N. *Tech. Dig. ECOC'2002*, 4.1.3 (2002).
5. Mollenauer L.F., Grant A.R., Mamyshev P.V. *Opt. Lett.*, **27**, 592 (2002).
6. Grant A.R. *IEEE J. Quantum Electron.*, **38**, 1503 (2002).
7. Kobtsev S., Pustovskikh A. *CLEO/Europe-2003, Europhysics Conference Abstracts*, **27E**, CL6-2-FRI (2003).

8. Xiao P., Zeng Q., Huang J., Liu J. *Photon. Tech. Lett.*, **15**, 206 (2003).
9. Ania-Castanon J.D., Kobtsev S.M., Pustovskikh A.A., Turitsyn S.K. *Proc. of LEOS XV Ann. Meet.* (Glasgow, Scotland, 2002, WQ4).
10. Kimura T., Nakae M., Yoshida J., Iizuka S., Sato A., Matsuura H., Shimizu T. *OFC-2002*, 485 (2002).