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Continuous-wave highly efficient phosphosilicate fibre-based Raman laser ($\lambda = 1.24$ μm)

E M Dianov, I A Bufetov, M M Bubnov, M V Grekov, A V Shubin, S A Vasil'ev, O I Medvedkov, S L Semenov, O N Egorova, A N Gur'yanov, V F Khopin, M V Yashkov, D Varelas, A Iocco, D Costantini, H G Limberger, R-P Salathe

Abstract. An efficient fibre-based Raman laser was developed on the basis of a phosphosilicate optical fibre with low optical losses. Bragg fibre gratings, constituting the laser cavity, were formed directly in the active fibre. The parameters, mathematical modelling, and optimisation of the laser were investigated. As a result of the optimisation, the output power reached 2.4 W for pumping with radiation from a neodymium fibre-based laser with a power of 3.5 W, which corresponds to a 77% quantum efficiency of the Raman laser.

1. Introduction

A trend towards expansion of the spectral range and introduction of systems with wavelength-division multiplexing has appeared recently in fibre-optic communication. Raman amplifiers, which have a broad amplification spectrum, are of special interest from this point of view. Their important advantage is the ability to operate (when the appropriate pump wavelength is selected) at any wavelength in the spectral range used in optical communication. Thus, a pump source with a wavelength of about 1.24 μm is needed to ensure amplification at a wavelength of 1.31 μm.

One of the possible pump sources for a Raman amplifier operating at $\lambda = 1.31$ μm is a Raman laser pumped by radiation from an Nd or Yb fibre laser and yielding, as a result, Raman Stokes radiation with $\lambda = 1.24$ μm. Several devices of this kind have been developed recently [1 – 3]. In a previous study [3] we proposed a Raman laser in which an optical fibre with a phosphorus-doped core (a phosphosilicate optical fibre) was used as the active medium instead of the germanosilicate optical fibre used traditionally [1, 2]. The Stokes shift of 1330 cm^{-1} (which exceeds by a factor of 3 the shift in the germanosilicate fibre) made it possible to avoid multistage Raman conversion and to generate the required wavelength of 1.24 μm already in the first Stokes component. Thus, an appreciable simplification of the laser system was achieved.

This communication reports a significant increase in the efficiency of a Raman laser, operating on the basis of a phosphosilicate optical fibre, as a result of lowering the distributed optical losses, of an increase in the Raman gain in the fibre, and of the optimisation of its length, as well because of formation of Bragg gratings directly in the active optical fibre [4].

As a result of improvements in the structure and fabrication technology of the phosphosilicate optical fibre, a significant reduction in the losses at the pump (α_p) and lasing (α_s) wavelengths was achieved together with a simultaneous increase in the Raman gain of the optical fibre (g_0). Fig. 1 presents the optical-loss spectra of an optical fibre with a 13% molar content of P_2O_5 in the core ($\Delta n \approx 0.01$) (curve *1*). The optical losses are $\alpha_p = 2.34$ dB km^{-1} and $\alpha_s = 1.45$ dB km^{-1} for $g_0 = 6.3$ dB km^{-1} W^{-1}. For comparison, Fig. 1 (curve *2*) gives the loss spectrum of a phosphosilicate optical fibre used previously [3]. For this optical fibre we found that $\alpha_p = 2.99$ dB km^{-1} and $\alpha_s = 2.26$ dB km^{-1} when $g_0 = 5.0$ dB km^{-1} W^{-1}.

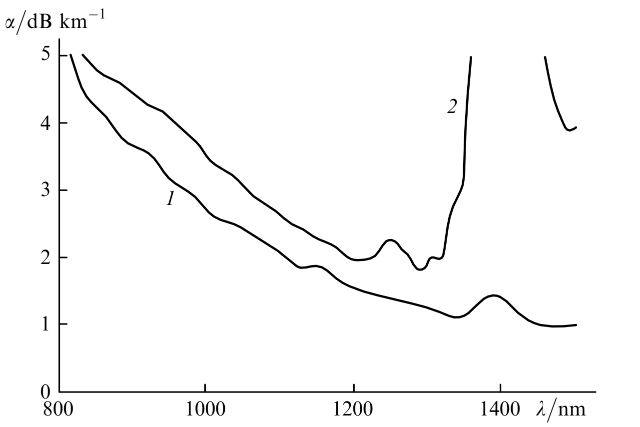

Figure 1. Optical loss spectra of a phosphosilicate optical fibre used in the present study (*1*) and in Ref. [3] (*2*).

2. Losses in the Raman-laser cavity

For a specified pump power, the efficiency of a fibre-based Raman laser is determined by the values of g_0, α_p, and α_s and also by the lumped losses in the cavity (to a large extent, these are the losses of the points where unlike optical fibres

E M Dianov, I A Bufetov, M M Bubnov, M V Grekov, A V Shubin, S A Vasil'ev, O I Medvedkov, S L Semenov, O N Egorova Scientific-Fibre Optics Centre at the Institute of General Physics, Russian Academy of Sciences, ul. Vavilova 38, 117942 Moscow, Russia;
A N Gur'yanov, V F Khopin, M V Yashkov Institute of the Chemistry of Very Pure Substances, ul. Tropinina 49, 603600 Nizhny Novgorod, Russia;
D Varelas, A Iocco, D Costantini, H G Limberger, R-P Salathe Institute of Applied Optics, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland

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are welded together). If Bragg gratings used as the cavity mirrors are not formed in the active optical fibre, then in general the cavity contains two weld points. One such point (and hence half of the lumped cavity losses) may be eliminated if a cleavage plane of the active optical fibre is used directly as the output mirror. The reflection coefficient of the output mirror is then determined by the refractive index of quartz glass and amounts to 3.5%. Both weld points can be eliminated when a Bragg grating is formed directly in an active optical fibre. We made Raman lasers based on a phosphosilicate optical fibre with a single weld point between the fibres in the cavity (laser I) and with a Bragg grating formed directly in the active optical fibre (laser II).

3. Investigation of laser I

The length of the active optical fibre in laser I was 1424 m (Fig. 2). A neodymium fibre laser was used as the pump source. A multiplexer played the role of a broad-band filter preventing lasing in the range $\lambda = 1.09-1.13$ μm, corresponding to the quartz Stokes shift in the Raman spectrum. A Bragg fibre grating with a reflection coefficient greater than 99% at $\lambda = 1.234$ μm, serving as the Raman-laser cavity mirror, was welded to the exit from the neodymium laser. The laser-cavity output mirror was the end-face, perpendicular to the phosphosilicate fibre axis.

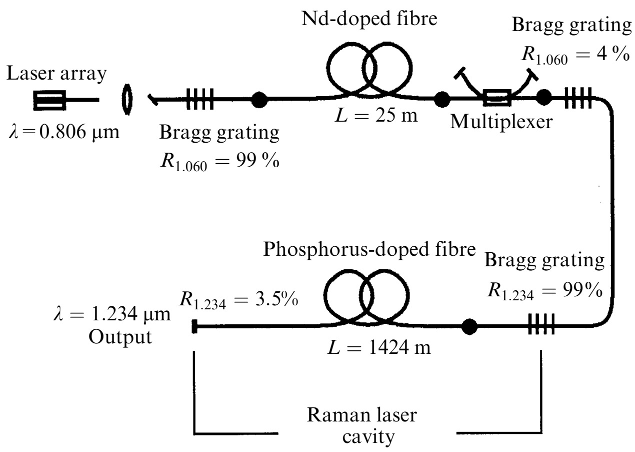

Figure 2. Schematic illustration of the fibre-based Raman laser I with the optical-fibre end face as the cavity output mirror. The circles indicate the weld points.

When the Nd laser was pumped by a diode array with a fibre output (OPC-D010-806-HB/250 model, power up to 10 W, $\lambda = 0.806$ μm), the laser radiation power was measured at the exit from the system at wavelengths of 1.06 and 1.234 μm. The pump power measured at the exit was recalculated as the power at the entry to the Raman laser on the basis of the known absorption coefficient of the phosphosilicate fibre. The relationships obtained are indicated by circles in Fig. 3. The maximum efficiency of the Raman laser, illustrated in Fig. 2, was ~44% for a pump power $P_{1.06} \approx 2.7$ W ($\lambda = 1.06$ μm). This fibre-based Raman laser system made it possible to determine g_0 of the phosphosilicate fibre. The low reflection coefficient of the output mirror was the principal source of the optical losses in the cavity, greatly exceeding both the distributed losses and the losses at the weld points. When the threshold power $P_{\text{th}\,1.06}$, the losses

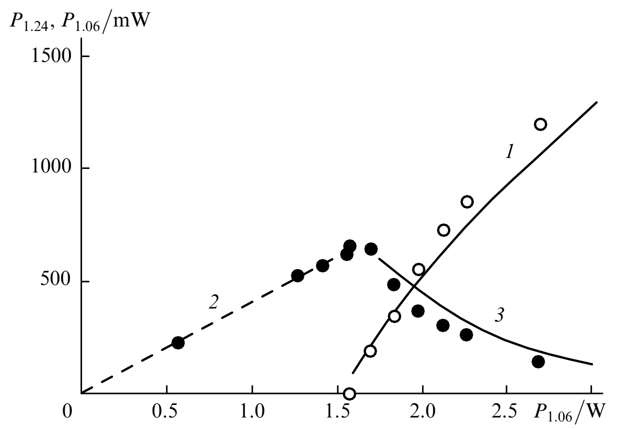

Figure 3. Experimental (circles) and theoretical (curves) dependences of the output power of the fibre-based Raman laser I on the pump power at the entry to a phosphosilicate optical fibre for $\lambda = 1.24$ (●, *1*) and 1.06 μm (○, *2, 3*).

α_{p} and α_{s}, the reflection coefficient of the exit end-face $R \approx 0.035$, and the fibre length L are known, we can determine g_0 with high precision from

$$g_0 = \frac{L\alpha_{\text{s}} + 5\lg(1/R)}{P_{\text{th}\,1.06} L_{\text{eff}}},$$

where

$$L_{\text{eff}} = \frac{4.34}{\alpha_{\text{p}}}\left[1 - \exp\left(-\frac{L\alpha_{\text{p}}}{4.34}\right)\right]$$

is the effective length of the phosphosilicate fibre [5]. In this case, the absolute error in determination of g_0 is governed mainly by the error in measurement of the threshold pump power (~5%). For the phosphosilicate fibre used in the present study, the Raman gain g_0 was approximately 6.3 dB km^{-1} W^{-1}.

4. Optimisation of the design of a Raman laser

The operation of the Raman laser was simulated mathematically on the basis of the measured parameters of the active optical fibre by using the familiar equations for the description of Raman scattering [5, 6]. The results of such a simulation of the operation of laser I are presented in Fig. 3 and they agree well with experiments, which makes it possible to use the same mathematical model for the optimisation of the Raman laser system.

The results of selection of the optimum length of the optical fibre are given in Fig. 4 in the form of three groups of curves which represent the dependences of the output power of the Raman laser on the lengths of the active fibre for a fixed pump power of 3.5 W. Within each group, the different curves correspond to different reflection coefficients of the Bragg output grating taken from the series 0.9, 0.8, 0.6, 0.4, 0.2, and 0.1. The groups of curves correspond to different lumped optical losses in the Raman laser cavity.

It follows from the results that a high efficiency of the fibre-based Raman laser may be attained for minimum lumped losses in the cavity and a minimum length of the active fibre, determined by the residual lumped losses (for example, the losses in the Bragg grating). The maximum output power, attainable from this optical fibre, is then determined mainly by α_{s}.

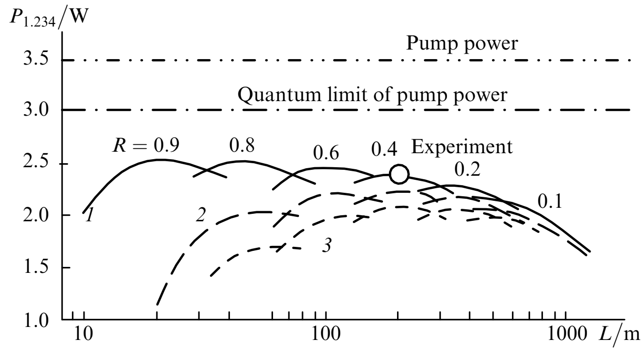

Figure 4. Dependences of the output power of a fibre-based Raman laser on the length of a phosphosilicate optical fibre calculated for different reflection coefficients R of the output Bragg grating. The pump power was $P_{1.06} = 3.5$ W and the lumped losses in the cavity were 0 (*1*), 0.05 dB (*2*), and 0.1 dB (*3*).

5. Formation of fibre Bragg gratings in a phosphosilicate optical fibre

Phosphosilicate fibres are not sufficiently sensitive to UV radiation with $\lambda = 248$ and 193 nm for the formation of gratings [7]. In order to increase the photosensitivity of such fibres, the latter are treated in an atmosphere of molecular hydrogen at a high pressure. A stable change in the refractive index in the optical-fibre core, of the order of 10^{-3} and more, then becomes possible on exposure to the radiation of an excimer ArF laser at $\lambda = 193$ nm [7].

In our experiments, the entire fibre 200 m long was subjected to the hydrogen treatment and then the required gratings were formed at its ends. The hydrogen treatment was carried out at a pressure of 150 bar and a temperature of 80 °C for 50 h. The fibre Bragg gratings were formed by the radiation of an excimer ArF laser (LPX-150, Lambda-Physik) transmitted by a phase mask, as suggested by Hill et al. [8]. During the formation of the gratings, the energy density on the fibre surface was 100 mJ cm^{-2}, the pulse repetition rate was 10 Hz, and the irradiation time was varied from 1 to 10 min, depending on the required grating reflection coefficient. The length of the gratings was 3 mm.

The spectral characteristics of the gratings were monitored directly during their formation. Under these conditions, the sources of the broad-band test radiation were optical diodes, whereas the transmission spectrum was recorded by a monochromator. In these measurements, the spectral resolution was 0.05 nm, which made it possible to record qualitatively their spectrum when the characteristic spectral width of the gratings was 0.5 nm. A typical dynamic range in the spectral measurements was 20 dB. The reflection coefficient of the gratings used as nontransmitting cavity mirrors then exceeded 20 dB, but it was not measured accurately.

After the formation of the gratings, the hydrogen remaining in the optical-fibre core must be removed, since the presence of molecular hydrogen dissolved in the glass induces an excess absorption in the range $\lambda = 1.05 - 1.3$ μm [9]. The optical fibre with a grating was kept at 80 °C for two days. After evolution of molecular hydrogen from the glass matrix, the loss spectrum of the fibre was remeasured. Its comparison with the initial spectrum showed that, in the spectral range which we employed, the hydrogen treatment and UV irradiation did not increase the losses within the limits of the error in measurement of the latter (0.1 – 0.2 dB). This was also confirmed by the results of our study of the lasing properties of the optical fibre.

6. Study of an optimised Raman laser

Our investigations made it possible to design a low-loss Raman laser based on a phosphosilicate optical fibre (laser II) in which the cavity fibre Bragg gratings were formed directly in the active fibre. The design of laser II is illustrated in Fig. 5. A section of an optical fibre 200 m long described above was used as the active medium. The fibre length was selected with the aim of compensating for the possible lumped losses induced during the formation of the Bragg grating.

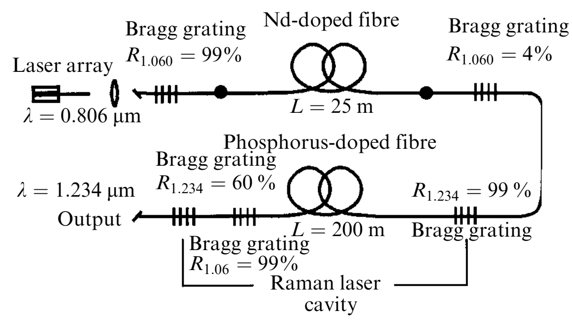

Figure 5. Schematic illustration of the fibre-based Raman laser II with a Bragg grating formed directly in a phosphosilicate optical fibre. The circles denote the weld points.

The laser was pumped at $\lambda = 1.06$ μm by a fibre neodymium laser and the output Bragg grating of the latter was also formed in a phosphosilicate optical fibre. In addition, a Bragg grating with a high reflection coefficient at $\lambda = 1.06$ μm, located at the exit from the Raman laser, was formed in the fibre. It returned to the active fibre the nonabsorbed part of the pump radiation and thus promoted its more efficient utilisation, reducing the lasing threshold of the neodymium laser. The fibre Bragg grating, acting as a nontransmitting neodymium-laser cavity mirror on the side corresponding to the injection of the pump at a wavelength of 0.806 μm, was formed in a section of a standard germanosilicate fibre of the Flexcore-1060 type and was welded to the neodymium optical fibre.

Fig. 6 gives the dependence of the output radiation power of a Raman laser with $\lambda = 1.234$ μm on the $\lambda = 1.06$ μm pump power at the entry to the phosphosilicate fibre. The maximum output power reached 2.4 W for a pump power of 3.5 W. The energy efficiency was 66% (and the quantum efficiency was 77%). The inset in Fig. 6 is the emission spectrum of this Raman laser.

The fibre-based neodymium and Raman lasers constituted a single device pumped by a laser-diode array, the total efficiency of which was 25% relative to the $\lambda = 0.806$ μm pump power. The dependences of the output power of the Raman lasers I and II on the pump power are plotted in Fig. 7. It is important to note that the optimised laser II had a very low Stokes-component emission threshold for the pump radiation with $\lambda = 0.806$ μm. It can be seen from the inset in Fig. 7 that this threshold was only 300 mW. This should make it possible to construct systems pumped by single multimode laser diodes with an output power of

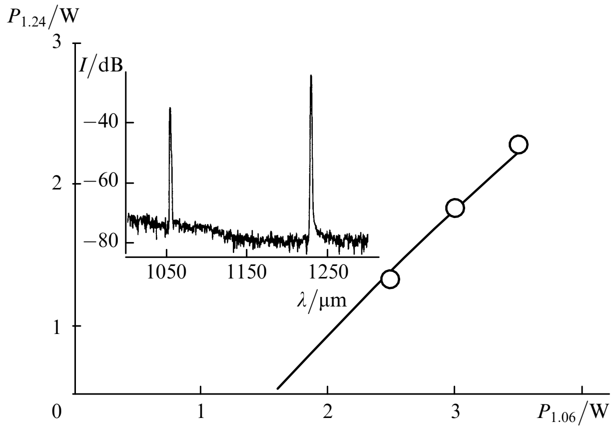

Figure 6. Dependence of the output power of a fibre-based Raman laser on the pump power at the entry to a phosphosilicate optical fibre. The inset is the output emission spectrum of the fibre-based Raman laser.

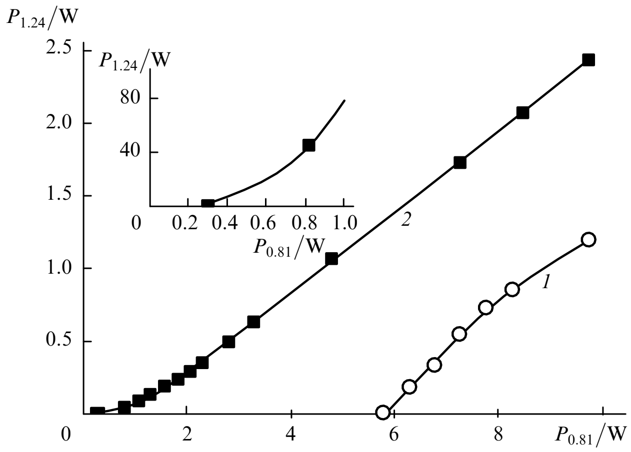

Figure 7. Dependence of the output radiation power with $\lambda = 1.24$ μm on the power of a laser-diode array with $\lambda = 0.806$ μm for lasers I (*1*) and II (*2*). The inset shows the threshold part of the relationship presented by curve *2*.

the order of 1 – 3 W, instead of using expensive high-power diode arrays. For such a pump power, the system described can provide an output power up to 600 mW at $\lambda = 1.24$ μm, which is sufficient to attain a gain of more than 25 dB in a fibre-based Raman amplifier [10].

7. Conclusions

The possibility of constructing a highly efficient Raman laser based on a photosilicate optical fibre with a Bragg grating, formed directly this fibre, was thus demonstrated for the first time in the present study. This became possible because of the availability of a phosphosilicate optical fibre with a high Raman gain ($g_0 = 6.3$ dB km^{-1} W^{-1}) and low losses ($\alpha_p = 2.34$ dB km^{-1} and $\alpha_s = 1.45$ dB km^{-1}. Optimisation increased the maximum quantum efficiency of a Raman laser with $\lambda = 1.234$ μm to 77% and the output power to 2.4 W.

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References

1. Grubb S G, Erdogan T, Mizrai V, Strasser T, Cheung W Y, Reed W A, Lemmaire P J, Miller A E, Kosinski S G, Nykolak G, Beker P C, Peckham D W *Proceedings of the Topical Meeting on Optical Amplifiers and their Applications, Breckenridge, OH, 1994* Paper PD3
2. Chernikov S V, Taylor J R, Platonov N S, Gapontsev V P, Kuppers F, Mattheus A, Gabitov I *Technical Digest of the Papers presented at the Optical Fiber Communication Conference (OFC'97), Dallas, TX, 1997*, Paper FA3
3. Dianov E M, Grekov M V, Bufetov I A, Vasiliev S A, Medvedkov O I, Plotnichenko V G, Koltashev V V, Belov A V, Bubnov M M, Semjonov S L, Prokhorov A M *Electron. Lett.* **33** 1542 (1997)
4. Dianov E M, Bufetov I A, Bubnov M M, Shubin A V, Vasiliev S A, Medvedkov O I, Semjonov S L, Grekov M V, Paramonov V M, Guryanov A N, Khopin V F, Varelas D, Iocco A, Costantini D, Limberger H G, Salathe R-P *Technical Digest of the Papers presented at the Optical Fiber Communication Conference (OFC'99), San Diego, CA, 1999*, Paper PD25
5. Agraval G P *Nonlinear Fiber Optics* (New York: Academic Press, 1989)
6. Shen Y R *Principles of Nonlinear Optics* (New York: Wiley, 1984)
7. Strasser T A, White A E, Yan M F, Lemaire P J, Erdogan T *Technical Digest of the Papers presented at the Optical Fiber Communication Conference (OFC'95), San Diego, CA, 1995*, pp 159 – 160
8. Hill K O, Malo B, Bilodeau F, Johnson D C, Albert J *Appl. Phys. Lett.* **62** 1035 (1993)
9. Lemaire P J *Opt. Eng. (Bellingham)* **30** 780 (1991)
10. Dianov E M, Grekov M V, Bufetov I A, Mashinsky V M, Sazhin O D, Prokhorov A M, Devyatykh G G, Guryanov A N, Khopin V F *Electron. Lett.* **34** 669 (1998)