Phosphosilicate-core single-mode fibers intended for use as active medium of Raman lasers and amplifiers

Olga N. Egorova, Mikhail M. Bubnov, I. A. Bufetov, Eugeni M. Dianov, Alexei N. Guryanov, et al.

Olga N. Egorova, Mikhail M. Bubnov, I. A. Bufetov, Eugeni M. Dianov, Alexei N. Guryanov, Vladimir F. Khopin, Sergey L. Semjonov, A. V. Shubin, "Phosphosilicate-core single-mode fibers intended for use as active medium of Raman lasers and amplifiers," Proc. SPIE 4216, Optical Devices for Fiber Communication II, (2 February 2001); doi: 10.1117/12.414125

Event: Information Technologies 2000, 2000, Boston, MA, United States

Phosphosilicate-core single-mode fibers intended for use as active medium of Raman lasers and amplifiers

O.N. Egorova[*a], M.M. Bubnov[a], I.A. Bufetov[a], E.M. Dianov[a], A.N. Guryanov[b], V.F. Khopin[b], S.L. Semjonov[a], A.V. Shubin[a]

[a]Fiber Optics Research Center at the General Physics Institute, Russian Academy of Sciences

[b]Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences

ABSTRACT

Highly phosphorus doped (7-17 mol %) single-mode fibers for the application in Raman laser have been manufactured. It has been established that with increasing the P_2O_5 concentration level, both optical losses and the fiber Raman gain coefficient increase. Using the fiber technology developed, the maximum efficiency of a single-cascaded Raman laser is achieved at a phosphorus pentoxide doping level of 12-14 mol % P_2O_5.

Keywords: Phosphorus doped fibers, Raman amplifier, Raman laser, MCVD technology.

1. INTRODUCTION

Cascaded Raman fiber lasers have recently acquired great importance as pump sources for Raman and Er-doped fiber amplifiers[1,2]. Such fiber lasers are commonly based on GeO_2-doped fibers, which feature a large Raman cross-section. However, in consequence of a rather small frequency shift of 440 cm^{-1} in germanosilicate glasses, several laser cascades must be used to create a fiber laser operating at 1.24µm and 1.48µm, the pump wavelengths for 1.3µm and 1.55µm fiber amplifiers. It was demonstrated[3] that the Raman laser design can be significantly simplified by using a phosphorus-doped fiber. The Raman shift in phosphorus pentoxide, which is due to the P=O bond vibration, is approximately three times greater than that in pure silica or germanosilicate glass (Fig.1). This fact allows one to reduce the number of laser cascades.

To create a highly efficient Raman laser, a heavily phosphorus-doped single-mode fiber with low optical losses is required. The gain coefficient and optical losses strongly depend on the phosphorus pentoxide concentration in the fiber core and on the fiber fabrication conditions. To provide effective laser operation, optimization of the above factors is required. In this paper, optical and gain characteristics of phosphosilicate fibers are measured at different phosphorus concentrations at the wavelength of 1.06 µm (the wavelength of the Nd fiber laser, which is commonly used to pump Raman fiber lasers) and at the wavelength of 1.24 µm, at which 1.3 µm amplifiers are pumped. The optimum fiber parameters were found using the Raman fiber laser model[4]. The phosphosilicate fibers manufactured by us are, to our knowledge, the best from standpoint of using them as an active laser medium.

2. FIBER PREFORM TECHNOLOGY

The fibers under this study were manufactured by the MCVD technique. The deposited cladding had an F-P_2O_5-SiO_2 composition, its refractive index being the same as that of pure silica or a little lower. In order to decrease optical losses, freon ($C_2F_3Cl_3$) was added into the gas mixture during the layer deposition[5]. An explanation of the fluorine co-doping influence on the fiber loss decrease is given in[6]. Fig. 2 shows the radial distribution of phosphorus pentoxide and fluorine determined by X-ray microanalysis. The maximum P_2O_5 concentration in the preform cross-section was in the range from 7 to 17 mol %.

*Correspondence: Email: egorova@forc.gpi.ru; Telephone: 7 (095) 135-7402; Fax: 7 (095)135-8139

Optical Devices for Fiber Communication II, Michel J. F. Digonnet, Osman S. Gebizlioglu, Roger A. Greenwell, Dennis N. Horwitz, Dilip K. Paul, Editors, Proceedings of SPIE Vol. 4216 (2001) © 2001 SPIE · 0277-786X/01/$15.00

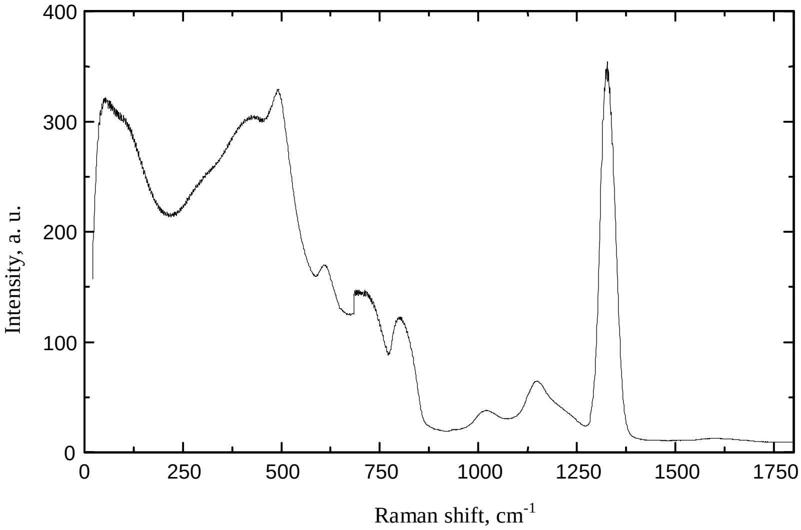

Fig.1. Raman spectra of 12 mol % doped phosphosilicate glass fiber.

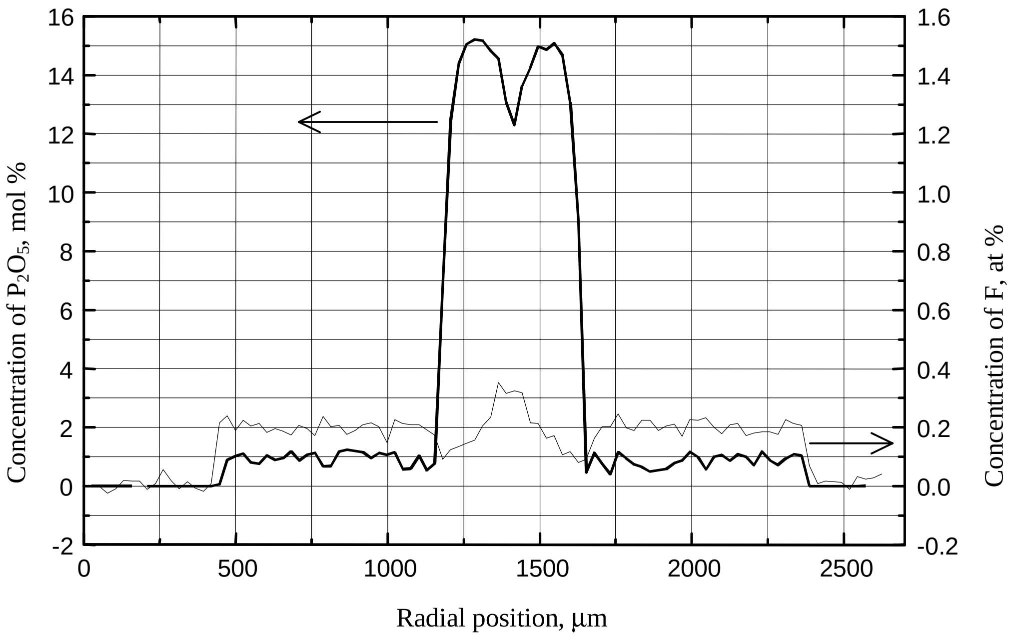

Fig. 2. Radial distribution of P_2O_5 and F in phosphosilicate preform.

High volatility and diffusion rate of phosphorus result in a significant reduction of phosphorus pentoxide concentration in the glass during preform collapsing and create a significant dip in the concentration and refractive index profile. Thus, a high concentration of phosphorus pentoxide can be achieved only with depositing a sufficiently thick layer of doped glass on the inner surface of the substrate tube. This results in an increase of the preform core diameter after collapsing. A high thermal expansion coefficient of phosphorus pentoxide doped glass[7] along with a large core diameter induce high internal stresses inside the preform. A rise of the maximum phosphorus pentoxide content in the core over 17 mol % leads to cracking of the preform core under the action of internal stresses. Therefore, the maximum concentration of phosphorus pentoxide in our preforms did not exceed 17 mol %.

3. OPTICAL LOSSES

To investigate the optical properties of fibers, we performed spectral measurement in the range of 600-1700 nm.

It is well know that the drawing temperature significantly influences optical losses of highly doped fibers[8]. To investigate this effect, fibers were drawn in a temperature range from 1940 to 1860^{0}C. Fig. 3 shows the dependence of optical losses on the drawing temperature for a fiber with 13 mol % of phosphorus pentoxide in the core. Decreasing the drawing temperature from 1940 to 1860^{0}C reduces optical losses and allows achieving 1.6 dB/km at 1.06 μm and 1.0 dB/km at 1.24 μm. To our knowledge, this is the best result for such fibers.

Fig.4 shows the dependence of optical losses on the phosphorus pentoxide concentration. The concentration was determined from the refractive index profile maximum and from the P_2O_5 molar refractivity obtained in[5]:

$$\Delta n = 0.88 \cdot 10^{-3} \cdot C(P_2O_5), \quad (1)$$

where Δn is the refractive index difference between pure and P_2O_5 doped silica, and $C(P_2O_5)$ is the concentration of phosphorus pentoxide expressed in molar percent. On increasing the phosphorus pentoxide concentration over 13 mol %, a fast growth of optical losses was observed (Fig.4). Similar optical loss behavior was observed earlier in high germanium doped fibers[8]; however, the origin of this increase is not clear.

Analysis of the loss spectrum of a fiber with 11 mol % of phosphorus pentoxide in the range 1.0 μm - 1.5 μm shows that phosphorus-doped fibers exhibit a λ^{-4} dependency. Thus, there are two main loss mechanisms: Rayleigh scattering and

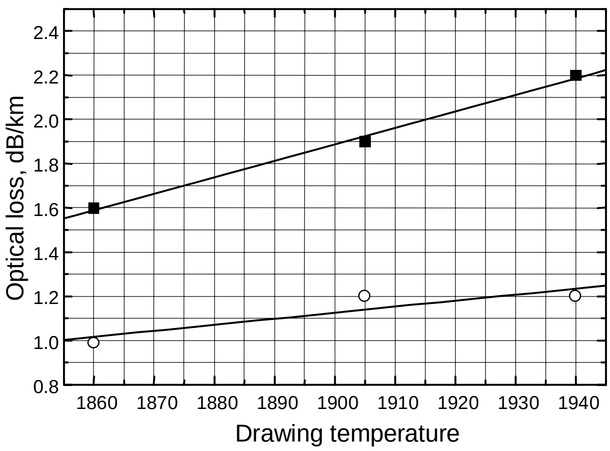

Fig.3. Optical losses of fiber with 13 mol % of phosphorus pentoxide measured at 1.06 μm (■) and 1.24 μm (○) versus drawing temperature.

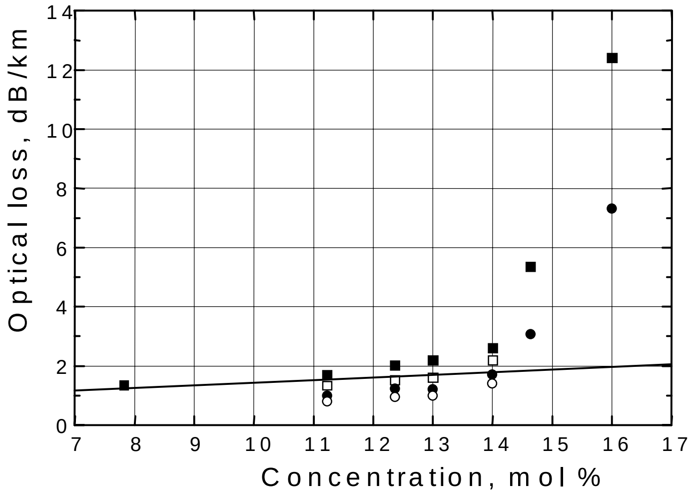

Fig. 4. Losses in fibers versus P_2O_5 concentration:

- ■ at 1.06 µm (fiber drawing temperature 1940^0C)
- □ at 1.06 µm (fiber drawing temperature 1860^0C)
- ● at 1.24 µm (fiber drawing temperature 1940^0C)
- ○ at 1.24 µm (fiber drawing temperature 1860^0C)

Solid line - evaluation of the minimum Rayleigh losses by means of linear approximation of the data for low-P_2O_5 fibers.

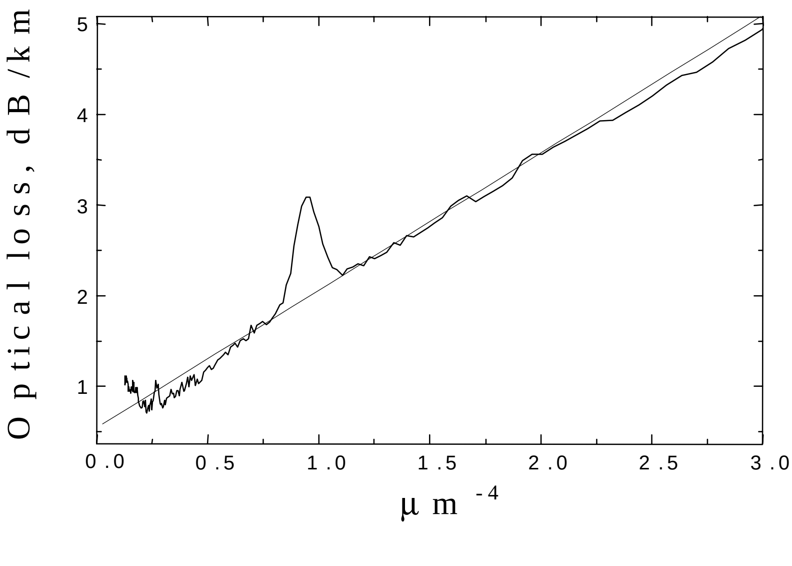

Fig.5. Optical loss spectra of 11 mol % doped phosphorus fiber versus wavelength^{-4}. The slope of the loss spectrum is the Rayleigh scattering coefficient.

wavelength independent loss (Fig.5). Evaluation of the minimum level of Rayleigh loss at 1.06 μm in Fig. 4 was made in the following way: the Rayleigh scattering coefficients were determined for the fiber with 11 mol % of phosphorus pentoxide and then a straight line was drawn to connect this Rayleigh loss value with that in pure silica[9] (0.5 dB/km). This linear fit was used to assess the Rayleigh loss in heavily phosphorus-doped fibers. The fact that the measured results significantly exceed the linear evaluation may be explained by the presence of non-Rayleigh concentration-dependent loss. A possible source of the additional losses is irregularities of the fiber structure. The irregularities in turn may result from the large difference of the physical characteristics of the fiber structure elements: the core and the reflecting cladding.

4. RAMAN GAIN COEFFICIENT AND P_F - PARAMETER OF PHOSPHOSILICATE FIBERS

A simple analytical expression for the quantum efficiency η_q of a multi-cascaded laser was obtained in[4]:

$$\eta_q = \left[1 - \sqrt{\frac{c}{4.3P_{p0}} \cdot P_F}\right]^2, \tag{2}$$

where c is the lumped loss in the fiber laser cavity (in dB), P_{P0} is the pump power. This formula was obtained for the case of optimum fiber length and output coupler reflectivity. The value of P_F depends only on the fiber characteristics and can be used as a criterion for choosing the best fiber parameters. As seen from (2), in order to increase the quantum efficiency of Raman fiber laser, the P_F-parameter should be as low as possible. For a single-cascaded Raman laser we have:

$$P_F = \left(\sqrt{\frac{\alpha_P}{g_0}} + \sqrt{\frac{\alpha_S}{g_0}}\right)^2, \tag{3}$$

where α_P, α_S are optical losses at the pump and signal wavelengths, g_0 is the fiber Raman gain coefficient (FRGC). P_F has a dimension of power. All values in (3) can be measured experimentally, which permits one to simplify predicting the fiber laser properties.

FRGC depends on the fiber characteristics. The relation between g_0 and G_R, the material Raman gain coefficient, which depends only on the phosphorus pentoxide concentration, follows from the well-known equation for Stokes power in a single-cascaded fiber Raman laser[10]

$$\frac{dP_S}{dz} = g_0 P_S P_P - \alpha_S P_S, \tag{4}$$

where P_S, P_P are signal and pump powers and z is the axial coordinate, and from a relation[11]

$$\frac{dI_S}{dz} = G_R I_S I_P - \alpha_S I_S, \tag{5}$$

where I_S, I_P are the signal and pump intensities.

FRGC in phosphosilicate fibers was measured at the wavelength of 1.234 μm, the pump radiation being at 1.06 μm (the experimental setup was described in[12]). So, the measured value of g_0 corresponds to the maximum value in the Stokes band shifted by 1330 cm^{-1}. The experimental method is based on measuring the pump power at the moment, when lasing is achieved.

The measured values of FRGC versus P_2O_5 concentration are presented in Fig. 6. The FRGC depends on the material gain coefficient, which is proportional to the P_2O_5 concentration, and on the mode field radial distribution. With decreasing phosphorus concentration, the core-cladding index difference also decreases leading to expansion of the mode spot size. As a result the dependence of g_0 on phosphorus concentration becomes non-linear.

Assuming that the refractive index linearly depend on concentration (1), the material gain coefficient G_R was estimated from the measured values of g_0 . The calculation was made with typical refractive index and concentration profiles. We obtained the following result Fig.7:

$$G_R \ m/W = 2.5 \cdot 10^{-15} \cdot C(P_2O_5) \ mol \ \%. \quad (6)$$

The dependence of the P_F-parameter calculated from (3) on the P_2O_5 doping level is shown in Fig. 8. This curve has a minimum at 12-14 mol %, which is the best-suited concentration for Raman laser. At low P_2O_5 concentrations, the fiber Raman gain coefficient decreases owing to a decrease of the material Raman gain coefficient, which is proportional to the P_2O_5 doping level, and owing to expansion of the mode spot size. This causes an increase in P_F at P_2O_5 concentrations below 12 mol %. At a high P_2O_5 doping level, optical losses rapidly increase in consequence of the corresponding P_F growth.

Decreasing the drawing temperature permits reduction of P_F (Fig. 8). It follows from Fig. 6 that the drawing temperature does not significantly affect RFGC. Slight variation of g_0 is probably due to refractive index profile distortion caused by drawing tension, which changes the mode field distribution. The value of the P_F -parameter goes down with decreasing the temperature owing to optical loss reduction. With the help of drawing temperature decreasing, a P_F-parameter of 0.91 W in fibers with 13 mol % of phosphorus pentoxide doping level was achieved. Fibers with the optimized properties were successfully used in single- and multi-cascaded Raman lasers[3, 12, 13, 14] .

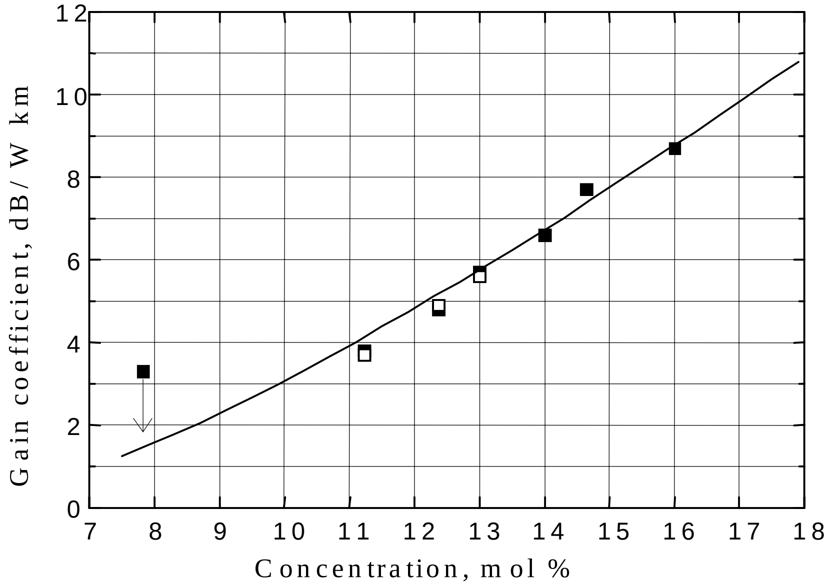

Fig.6. Fiber Raman gain coefficient at 1.24μm with the pump at 1.06μm versus maximum P_2O_5 concentration.
■ fiber drawing temperature 1940^0C
□ fiber drawing temperature 1860^0C
solid line – calculated values.

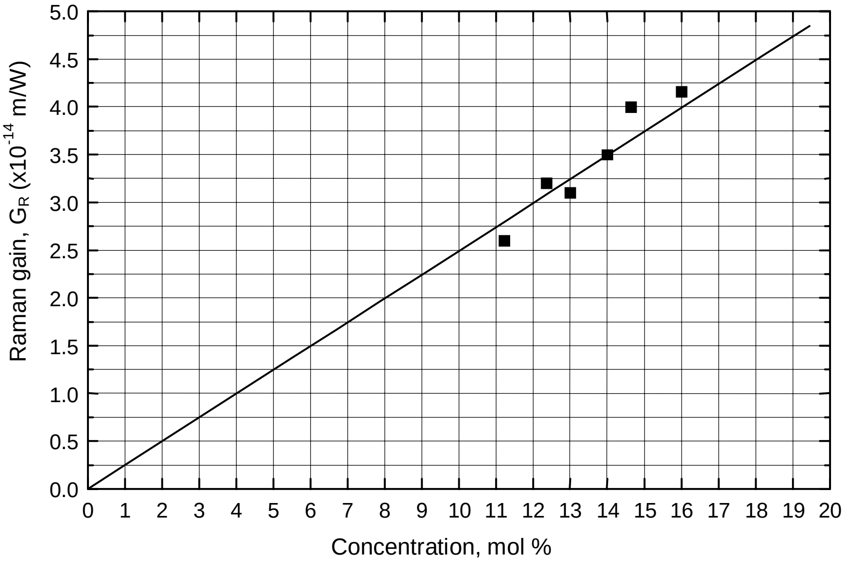

Fig.7. Material gain coefficient versus P_2O_5 concentration
■ measured values,
solid line – linear fit.

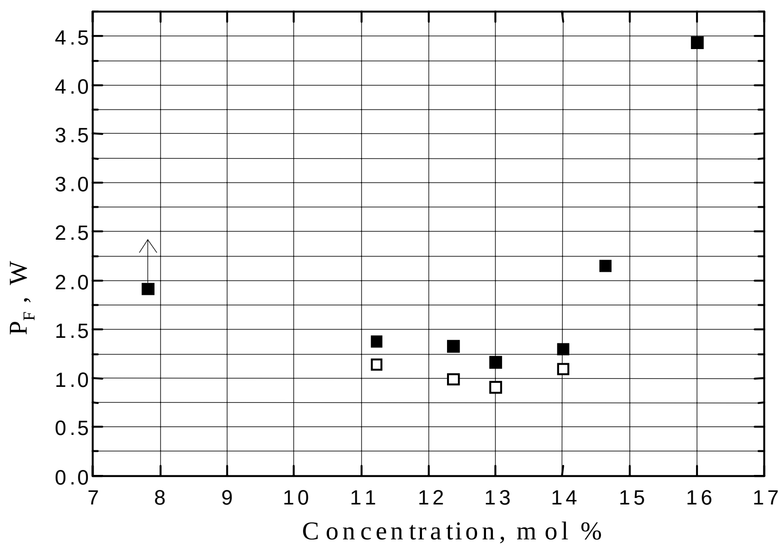

Fig.8. P_F-parameter of phosphosilicate fiber versus P_2O_5 concentration.
■ fiber drawing temperature 1940^0C
□ fiber drawing temperature 1860^0C

5. CONCLUSION

Raman fiber laser efficiency strongly depends on fiber characteristics. In this paper, P_F - parameter was used as a criterion for choosing the best-suited fiber characteristics. The value of the P_F-parameter, which has a dimension of power, is determined by optical losses and Raman fiber gain coefficient (RFGC) of the fiber. To increase the fiber laser efficiency, the P_F - parameter should be lowered.

For the first time, we measured RFGC and optical losses in a wide range of phosphorus pentoxide concentration (7 - 16 mol %). Our experimental results showed that at the current fiber technology level the best Raman fiber laser efficiency is achieved with fibers containing 12-14 mol % of P_2O_5. For a 13 mol % P_2O_5 doped fiber drawn at 1860^0C, typical parameters are as follows: optical losses are 1.6 dB/km at 1.06 μm and 1.0 dB/km at 1.24 μm, g_0= 5.6 dB/km·W, P_F = 0.91 W. These parameters are, to our knowledge, the best results obtained so far for phosphosilicate fibers. Further increasing Raman fiber laser efficiency can be achieved by lowering additional concentration-dependent losses, which appear not to be of Rayleigh nature.

REFERENCES

1. E.M. Dianov, D.G. Fursa, A.A. Abramov, M.I. Belovolov, M.M. Bubnov, A.V. Shipulin, A.M. Prokhorov, G.G. Devyatykh, A.N. Gyr'yanov, and V.F. Khopin, "Raman fiber-optic amplifier of signals at the wavelength of 1.3 μm", *Quantum Electronics*, **24**, pp. 749-751, 1994.
2. S.G. Grubb, T. Erdogan, V. Mizrahi, T. Strasser, W.Y. Cheung, W.A. Reed, P.J. Lemaire, A.E. Miller, S.G. Kosinski, G. Nykolak, P.C. Becker, and D.W. Peckham, "1.3 μm cascaded Raman amplifier in germanosilicate fibers", *Proc. Opt. Amplifiers Their Appl.*, CO, Paper PD-3, 3-5 August, Breckenridge, 1994.
3. E.M. Dianov, M.V. Grekov, I.A. Bufetov, S.A. Vasiliev, O.I. Medvedkov, V.G. Plotnichenko, V.V. Koltashev, A.V. Belov, M.M. Bubnov, S.L. Semjonov and A.M. Prokhorov, "CW high power 1.24 μm and 1.48 μm Raman lasers based on low loss phosphosilicate fiber", *Electron. Lett.*, **33**(18), pp. 1542-1544, 1997.
4. I.A. Bufetov, E.M. Dianov, "Simple analytical model of CW multi-cascaded Raman fiber laser", *Quantum Electronics*, **10**, 2000.
5. M.M. Bubnov, E.M. Dianov, O.N. Egorova, S.L. Semjonov, A.N. Guryanov, V.F. Khopin, E.M. DeLiso "Fabrication and investigation of highly phosphorus-doped fibers for Raman lasers", *Proceedings of SPIE*, 4083, pp. 12-22, 2000.
6. A.N. Guryanov, L.A. Ketcova, V.F. Khopin, M.M. Bubnov, E.M. Dianov, O.N. Egorova, S.L. Semjonov, "Influence of fluorine codoping on optical losses in Ge- and P-doped fibers", this volume.
7. E. Modon, G. Parisi, G. Roba, "Very low-loss and highly reproducible optical fibers by a pressurized M.C.V.D. method", *Alta Frequenza*, **LII**(2), pp. 98-102, 1983.
8. A.A. Abramov, M.M. Bubnov, E.M. Dianov, S.L. Semjonov, A.G. Schebunjaev, A.N. Gurjanov, V.F. Khopin, "The effect of fluorine co-doping on scattering and absorption properties of highly germanium-doped silica glass", *Proceeding of 17 International Congress of Glass*, 7, pp. 70-75, Chinese Ceramic Society, Beijing,1995.
9. R. Olshansky, "Propagation in glass optical waveguides", *Reviews of Modern Physics*, **51**(2), pp. 341-367, 1979.
10. J. Auyung, A. Yariv, "Theory of CW RAMAN oscillation in optical fibers", *J. Opt. Soc. Am.*, **69**(6), pp. 803-807, 1979.
11. G.P. Agrawal, *Non linear fiber optics*, Academic Press, 1989.
12. E.M. Dianov, I.A. Bufetov, M.M. Bubnov, M.V. Grekov, A.V. Shubin, S.A. Vasiliev, O.I. Medvedkov, S.L. Semjonov, A.N. Gur'yanov, V.F. Khopin, "Investigation of CW highly efficient 1.24 μm Raman laser based on low-loss phosphosilicate fiber", *Proc. Ecoc'99*, 1, pp. 72-73, Nice, France, 1999.
13. V.I. Karpov, E.M. Dianov, V.M. Paramonov, O.I. Medvedkov, M.M. Bubnov, S.L. Semjonov, S.A. Vasiluev, V.N. Protopopov, O.N. Egorova, V.F. Hopin, A.N. Guryanov, M.P. Bachynski, W.R.L. Clements, "Laser-diod-pumped Phosphosilicate-fiber Raman laser with an output power of 1 W at 1.48 μm", *Optics Letters*, **24**(13), pp. 887-889, 1999.
14. E.M. Dianov, I.A. Bufetov, M.M. Bubnov, M.V. Grekov, S.A. Vasiliev, and O.I. Medvedkov, "Three-cascaded 1407-nm Raman laser based on phosphorus-doped silica fiber", *Optics Letters*, **25**(6), pp. 1-3, 2000.