Medium-Power CW Raman Fiber Lasers

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Invited Paper

***Abstract*—A review of recent results on medium-power CW Raman fiber lasers pumped by laser diodes is presented. Most attention is given to Raman lasers based on phosphosilicate fibers, the latter providing a number of advantages compared to commonly used germanosilicate fibers.**

***Index Terms*—Fiber lasers, phosphosilicate fibers, Raman lasers.**

I. Introduction

ONE OF the bright achievements of laser physics in the 1990s was the creation of highly efficient medium-power continuous-wave (CW) single-mode Raman fiber lasers for the near infrared. The lasers can generate radiation practically at any wavelength in the region of 1.1–1.6 μm with high quality output power typical of several watts.

The initial driving force for the development of these lasers was to meet the requirements in CW sources for pumping 1.3-μm Raman fiber amplifiers [1], [2]. However, it has become clear that Raman fiber lasers are a promising pumping source for other optical fiber amplifiers, including Er-doped fiber amplifiers. Wide applications of optical amplifiers in optical fiber communication systems, especially in wavelength-division multiplexing (WDM) ones, stimulated great efforts to explore Raman fiber lasers.

Three recent achievements in fiber optics permitted the development of advanced CW Raman fiber lasers.

1) The observation of the efficient stimulated Raman scattering (SRS) in low-loss single-mode optical fibers [3].
2) The development of Nd (Yb)-doped double-clad fiber lasers (DCFL) pumped by laser diodes [4].
3) The discovery of the photosensitivity of optical fibers and the creation of the technique for in-fiber Bragg gratings (FBGs) formation [5], [6].

One of the first experiments with newly developed low-loss silica fibers was the experiment on SRS carried out by Stolen, *et al.* in 1971 [3]. The authors, for the first time, experimentally observed the stimulated Raman emission in a single-mode glass fiber. Stimulated scattering was obtained both as single-pass super-radiant emission and as output from an oscillator. The oscillator was constructed by using a 190-cm length of 4-μm core diameter single-mode fiber as an active medium and two mirrors. The second harmonic radiation (532 nm) of a pulsed Nd : YAG laser was used for pumping Raman oscillator. The threshold for oscillation was high, about 500 W of power in the fiber. One of the reasons for the high threshold was the damage-induced optical losses in the fiber. After this pioneer work a great interest was shown in the development of Raman fiber oscillators in the second half of the 1970s. This interest is explained by two reasons:

1) By the advantages of Raman fiber oscillators which utilize both long interaction lengths possible in low-loss optical fibers and broad Raman gain bandwidth in glasses ($\sim$500 cm^{-1}).
2) In the middle of the 1970s various low-loss optical fibers were developed and easily available.

As the result of wide researches low-threshold tunable Raman oscillators for both visible [7]–[10], and near IR [11], [12] regions were created. The fabrication of high-quality low-loss fibers helped reduce both the threshold (<1 W) and the problems of fiber-deterioration [8]. Tuning over 350 Å in the 5200–5600 Å spectral range was obtained using four orders of Stokes oscillation [10], [32].

The obtained experimental results pointed to the possible use of laser diodes to pump Raman fiber oscillators. The combination of a laser diode pump and a Raman fiber oscillator would result in a compact, efficient and inexpensive source for the near infrared. However, the problem was to achieve an efficient coupling of laser diode radiation to a single-mode fiber core. This problem has been solved by the development of Nd (Yb)-DCFLs pumped by laser diodes.

H. Po, *et al.* suggested a double-clad structure of the active fiber to ease laser diodes pumping [4]. The active single-mode core is surrounded by a cladding and this configuration forms the core of a multimode waveguide which is in its turn surrounded by an outer cladding of still lower refractive index. This multimode structure guides pump light around and through the central rate-earth-doped single-mode core. The shape and the dimensions of the inner cladding are chosen to provide efficient end-coupling of the output from high-power laser diode arrays. As a result, high power [up to 35 W CW] difraction-limited Nd (Yb)-doped fiber lasers operating at the wavelengths around 1 μm have been developed (see for example [13]–[15]) and turned out efficient pump sources for Raman fiber lasers.

FBGs are one of the critical elements of modern Raman fiber lasers. It has been found that it is possible to efficiently convert CW radiation of high-power double-clad fiber lasers to as

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many as six Raman–Stokes orders by utilizing highly reflective in-FBGs as mirrors for Stokes cavities [16]. In this way, each intermediate Raman–Stokes can be resonated and thereby efficiently converted to the next higher Stokes order until the cascade is terminated by suitable output coupling at the desired order. Thus, utilizing FBGs allowed to transform a bulky set-up of the multiresonant Raman fiber oscillator [10], [32] into an elegant all-fiber structure.

Below, we will discuss in detail recent results on the research and development of CW Raman fiber lasers which are produced now by a number of companies.

II. Medium-Power CW Raman Fiber Lasers

In the 1990s several ways to construct efficient Raman fiber lasers were explored. The lasers differed mainly by the type of fibers which had various Stokes frequency shifts, by the design of Stokes cavities, and by the pumping sources.

A. Raman Lasers on the Base of Germanosilicate Fibers

Germanosilicate fibers are an advantageous active medium for Raman fiber lasers. The technology of the fibers is well developed and there is mass production of low-loss germanosilicate fibers.

These fibers possess high photosensitivity, so it is possible to write Bragg gratings directly in them. The Raman scattering cross-section in germanosilicate fibers is higher compared to silica fibers and it increases as well as the photosensitivity with the increasing Ge content.

It was natural that germanosilicate fibers were used to construct cascaded CW Raman fiber lasers [1], [2]. Pumping a high Ge-doped fiber by a 1060-nm Nd : YAG laser, a 1239-nm 300-mW CW third-Stokes radiation was obtained and used for the first time to pump a 1.3 μm Raman fiber amplifier [1]. In the first demonstration of a CW diode-pumped Raman fiber laser [2], 800 m of a germanosilicate fiber were used. The fiber was H_2 sensitized to increase the photosensitivity. Three pairs of Bragg gratings forming the Stokes cavities were written directly in the germanosilicate fiber. The pump source was a diode-pumped Nd DCFL of 1060 nm.

With a 20% output coupler at the third Stokes frequency ($\lambda = 1240$ nm), a threshold of 175 mW and a slope efficiency of 53% were obtained. This Raman fiber laser was used for pumping a 1.3 μm Raman fiber amplifier.

A fifth-order cascaded Raman laser operating at the wavelength of 1480 nm was constructed with high-delta germanosilicate fiber as a Raman gain medium [16]. Five pairs of Bragg gratings were written in H_2 sensitized fiber. The pump source was a diode-pumped Yb DCFL at 1117 nm. With a 20% output coupler at the fifth Stokes frequency ($\lambda = 1484$ nm) a threshold of 660 mW, a slope efficiency of 46%, and an output power of 1.5 W were obtained. The laser can be used to pump high-power and remotely-pumped Er-doped fiber amplifiers.

Still more impressive results on Raman fiber lasers were reported by Innis, *et al.* [15]. The authors were able to obtain 8.5 W output power at 1472 nm pumping a fifth-order cascaded Raman laser with a 20.5 W Yb double-clad fiber laser at 1101 nm.

There is one more approach for constructing cascaded Raman fiber lasers, namely the utilization of fused WDM couplers to form Raman cavities [17], [18]. A cascaded Raman laser at 1240 nm was demonstrated with a 1060-nm Yb fiber laser as a pump source [17]. The other paper [18], describes a 1480-nm Raman fiber laser using both a fused WDM coupler and Bragg gratings. The pump source was a Nd : YLF laser operating at 1313 nm. A high Ge-doped fiber was used as an active Raman medium in both works. The efficiency of the cascaded Raman lasers with fused WDM couplers turned out to be less than the one of the lasers with Bragg gratings [2], [15], [16].

In spite of incontestable success in the development of cascaded Raman lasers based on germanosilicate fibers, there is one principal drawback of these lasers. It is connected with a relatively small Raman frequency shift equal to ~440 cm^{-1}. As we have already mentioned high-power, difraction-limited, diode-pumped Nd- or Yb-doped fiber lasers operating around 1 μm are the most promising pumping source for Raman fiber lasers. On the other hand at present it is 1450–1480-nm Raman fiber lasers which are in great demand for pumping optical amplifiers (Er-doped and Raman) in the 1.55-μm spectral window. It means that one needs to efficiently convert 1 μm-radiation to as many as six Stokes orders. That is, to write up to six pairs of Bragg gratings in a fiber. However, this makes the laser design too complicated and reduces the conversion efficiency.

The best option would be a fiber with a large enough Stokes frequency shift to obtain longer wavelength radiation using Raman–Stokes of lower orders. Besides, it should be sufficiently photosensitive to obtain highly reflecting Bragg gratings. It is interesting to note, that in the early 1980s researchers from AT&T Bell Laboratories explored a possibility to create a Raman fiber laser for 1.55-μm spectral region pumped by a 1060-nm Nd : YAG laser (see [19] and references in it). The active medium was molecular D_2 diffused into a 100-m-long single-mode germanosilicate fiber. The Raman shift of D_2 is 2972 cm^{-1} and the authors obtained the laser radiation at 1560 nm. After diffusion, the fiber was stored in liquid nitrogen at which temperature D_2 out-diffusion is negligible. So the fiber couldn't be used for wide practical applications.

It turned out that the above mentioned requirements are met by phosphosilicate fibers. The Raman spectrum of a phosphosilicate fiber shows a strong line shifted by 1330 cm^{-1} [20]. In addition, it has been shown that it is possible to write Bragg gratings directly in a phosphosilicate fiber by 193-nm radiation [21]. We suggested to use low-loss high P-doped fibers as an active medium for a Raman fiber laser [22]. In the first experiment, the radiation of the first and the second Stokes orders were obtained at 1.24 and 1.48 μm correspondingly pumping a phosphosilicate fiber by the radiation from 1060-nm Nd : YAG laser [23]. The obtained preliminary results have shown good prospects of phosphosilicate fiber-based Raman fiber lasers.

B. Raman Lasers on the Base of Phosphosilicate Fibers Using the 1330 cm^{-1} Stokes Frequency Shift

The main problem with a phosphosilicate fiber containing more than 10 mol % of P_2O_5 was a high level of optical losses. Thorough investigations on technology of phosphosilicate fibers

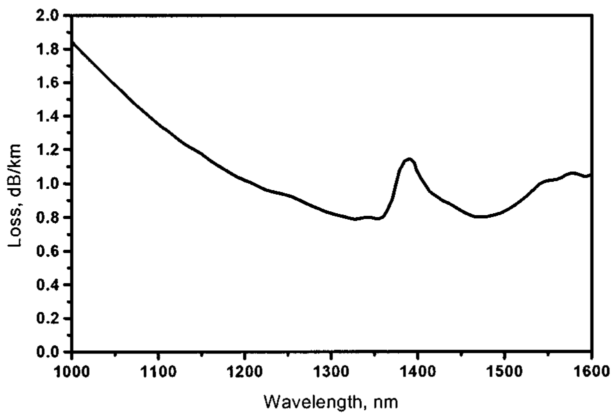

Fig. 1. Loss spectrum of a phosphosilicate fiber with the P_2O_5 content of 13 mol %.

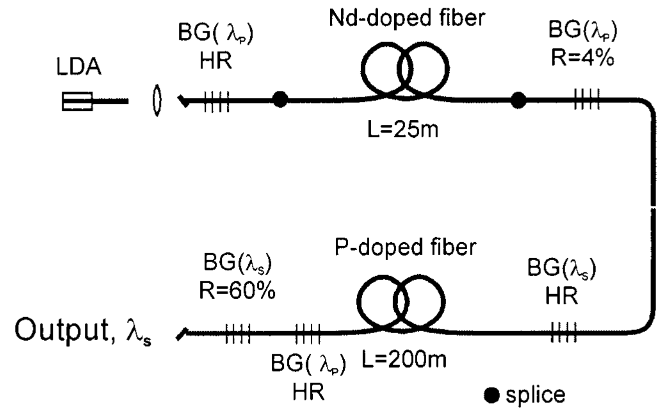

Fig. 3. Schematic of the 1240-nm Raman fiber laser.

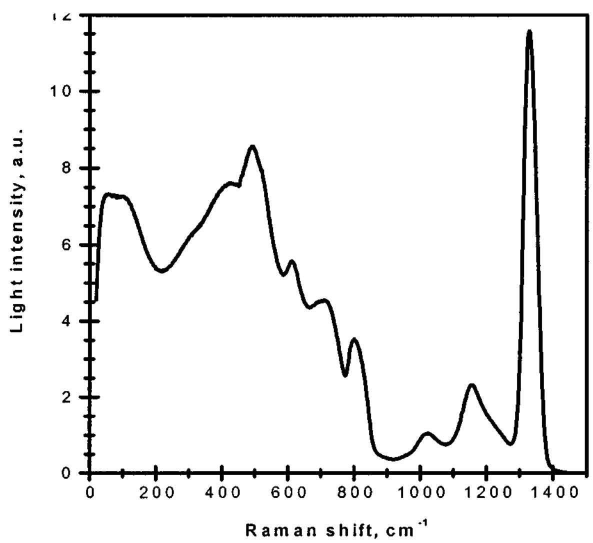

Fig. 2. Raman spectrum of the phosphosilicate fiber.

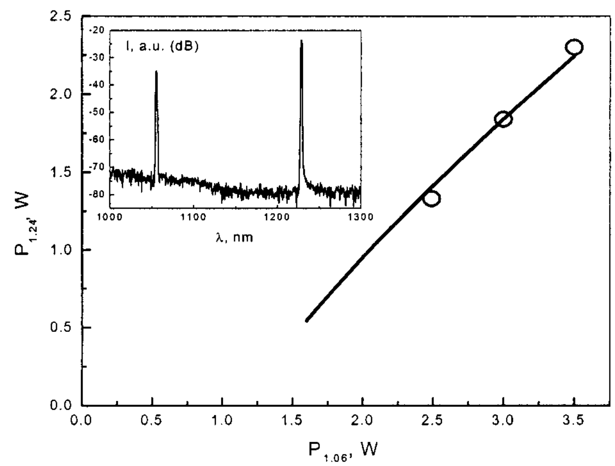

Fig. 4. Dependence of the 1.24-μm output power of the Raman laser on the 1.06 μm pump power. ○—experimental points, solid line-numerical simulation.

allowed to reduce optical losses to the level of $\leq$1 dB/km for the spectral region of 1.2–1.6 μm [24].

Fig. 1 shows a loss spectrum of a phosphosilicate fiber with the P_2O_5 content of 13 mol %. Fig. 2 shows the Raman spectrum of the phosphosilicate fiber. The spectrum consists of a narrow line related to $P = 0$ bonds and shifted by 1330 cm^{-1} and a broad band with the maximum at 490 cm^{-1} consisting in its turn of overlapping, SiO_2-related and P_2O_5-related components [25]. So, it is possible to construct Raman fiber lasers using both SiO_2- and P_2O_5-related frequency shifts ($\sim$490 cm^{-1} and 1330 cm^{-1}, correspondingly) to get new wavelengths of laser radiation.

Below, the recent results on the development of efficient phosphosilicate fiber-based Raman lasers with the generation wavelengths of 1.24, and 1.48 μm are presented.

1) CW 1240-nm Raman Fiber Laser [26], [27]: A schematic of the Raman fiber laser pumped by a Nd fiber laser is shown in Fig. 3.

As an active fiber, a phosphosilicate fiber with P_2O_5 content of 13 mol % ($\Delta n = 0.011$) and a length of 200 m has been used. To improve fiber photosensitivity for grating writing directly in the phosphosilicate fiber, we loaded it with hydrogen during four days under the pressure of 150 bars at the temperature of 50 °C. The gratings were written with the help of an ArF excimer laser (193 nm) using a phase mask technique. Irradiation conditions were as follows: energy density of 100 mJ/cm^2 and repetition rate of 10 Hz. The length of the gratings was 4 mm.

Fig. 4 shows 1240-nm output power versus 1.06-μm pump power. It can be seen that the maximum output power is 2.3 W at the pump power of 3.5 W. A quantum efficiency of 77% was observed, and it exceeds substantially the published results for the lasers based on germanosilicate fibers [2], [17]. The inset in Fig. 4 shows the output spectrum of the laser.

2) CW 1.48-μm Raman Fiber Laser [28]: Fig. 5 shows the experimental setup, consisting of a pigtailed LD array pump module, a Yb-doped double-clad fiber laser, and a 1.48-μm cascaded Raman converter. The pump light is launched into the first cladding of the Yb fiber through a short piece of standard fiber (Flexcor 1060 with low-index polymer coating, length $\approx$1 cm) with a highly reflecting 1.06-μm Bragg grating written in the core. The piece of Flexcor 1060 fiber served as a multimode waveguide for the pump radiation. The output coupler of Yb fiber laser was formed by a 5% Bragg grating. The estimated mode field diameters (MFDs) of the Yb fiber and the standard fiber at 1.06 μm were 6.9 and 7.1 μm, respectively,

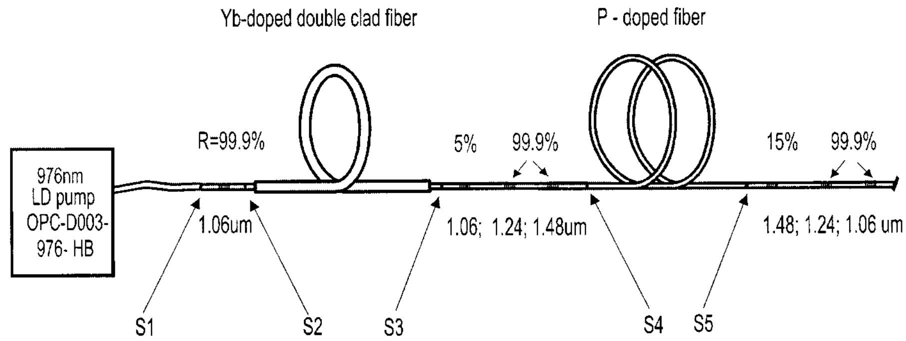

Fig. 5. Experimental set-up of 1.48-μm two-cascaded Raman laser pumped by Yb-doped double-clad fiber laser.

and permitted splicing of these fibers (splicing points S2 and S3) with an optical loss of 0.1 dB. The length of the Yb-doped double-clad fiber was 13 m, long enough to absorb the pump radiation at 976 nm. The mean diameter of the first cladding was 125 μm. The multimode pump is transformed into high-brightness 1.06-μm radiation with a slope efficiency of 80%. The laser emits 3.3 W of power at a maximum LD array power of 4.5 W, corresponding to a total light-to-light efficiency of 73%.

A cascaded resonant Raman laser cavity was formed by two pairs of Bragg gratings with a phosphosilicate fiber between them. All the gratings were written in Flexcor fiber after H_2 preloading. The reflectivity of the Raman laser gratings was $>$ 99%, except that of the 1.48-μm output coupler, which was 15%. A small nonresonant excess loss of approximately 0.1–0.15 dB was found in each of the two chains that consisted of three Bragg gratings. The phosphosilicate fiber was 1-km long. The fiber core contains $\sim$13 mol % of phosphorous, yielding a refractive-index difference of 0.011. The optical losses of the fiber length were 1.7, 1.0, and 0.8 dB at 1.06, 1.24, and 1.48 μm, respectively. The P_2O_5-doped fiber had MFDs of 6.3 and 10.4 μm at 1.06 and 1.48 μm, whereas the corresponding MFDs in the Flexcor fiber were 7.1 and 12.7 μm, respectively. In spite of the mismatched MFDs, by optimizing the splicing conditions we achieved an optical loss of only 0.05 dB when we spliced these fibers (splices S4 and S5).

Fig. 6 shows the emission spectrum measured at the output of the Raman laser when the total output power was 1.1 W. An important feature of the spectrum is the lack of silica Stokes (440-cm^{-1}) peaks at 1.12 and 1.31 μm, which means that it is not necessary to use rejection filters such as long-period fiber gratings to suppress the silica Stokes peaks.

The suppression of the 1.24-μm radiation corresponding to the first phosphorous Stokes order is 20 dB. The output power of the second-order phosphosilicate Stokes is shown in Fig. 7. The threshold for 1.24-μm radiation is $\sim$0.7 W. The 1.24-μm output increases with the pump power until the second Stokes threshold of 1.5 W is reached, and it is then clamped at a level of 10 mW. The slope efficiency of the 1.48-μm radiation with respect to the LD array power is 34%. The output power of 1 W is reached at a pump power of 4.5 W. At this point, the spectral width of the 1.48-μm radiation is 0.75 nm (FWHM).

The LD-pumped Yb laser developed has a slope quantum efficiency of $\sim$90%, and it seems that the further improvement in the 1.48-μm laser efficiency is associated mainly with reducing the Raman cavity's loss.

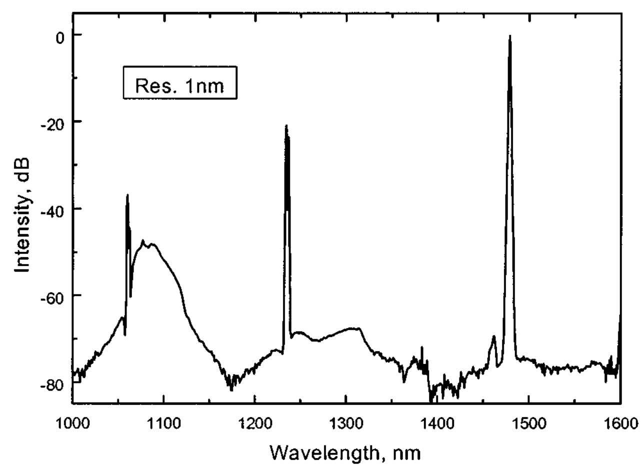

Fig. 6. Emission spectrum at the output of the 1480-nm Raman converter.

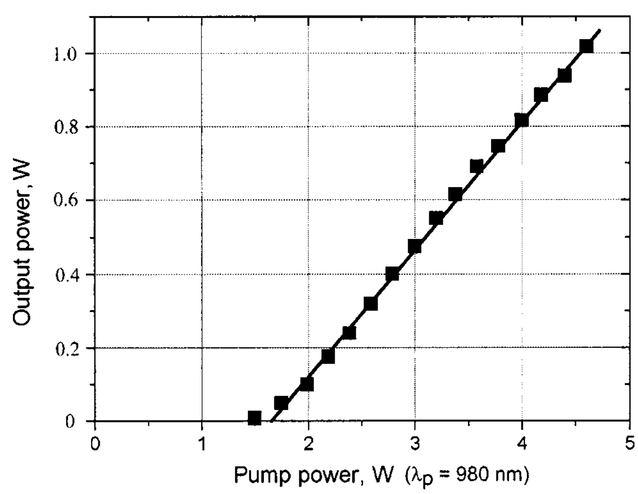

Fig. 7. The power of the second-order Stokes at the output of the Raman converter versus pump power.

The calculated dependence of the output power on the length of the phosphosilicate fiber is shown in Fig. 8 for two values of excess losses. In these computer simulations, we used the spectral attenuation and index profile of the fiber that were used in the experiment. The excess loss includes the splicing loss at points S4 and S5, and the nonresonant loss in the two fiber grating chains. The calculations indicate that, for an excess loss of 0.15 dB (as in the experiment), the output power could exceed 1.2 W if the fiber length were reduced to 400 m. Further

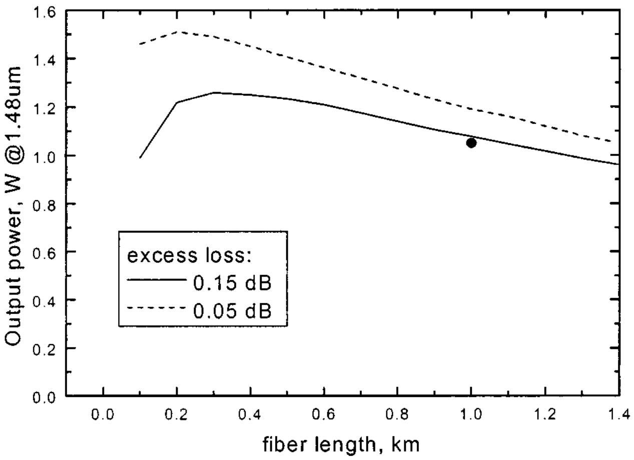

Fig. 8. Calculated output power of the 1.48-μm laser versus fiber length for two values of excess loss (pump power 3 W @ 1060 nm). •—experimental result.

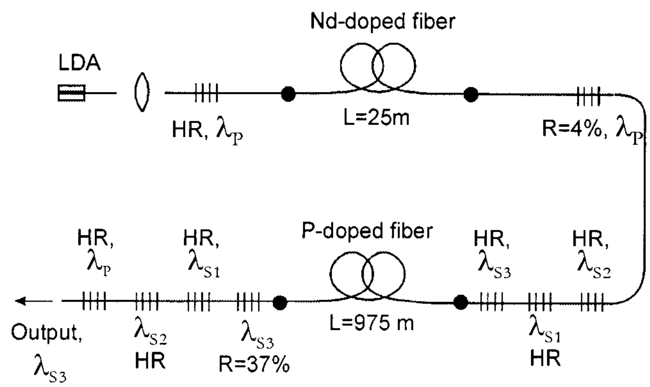

Fig. 9. The scheme of the three-cascaded Raman laser, based on phosphosilicate fiber, pumped by the Nd-doped double-clad fiber laser.

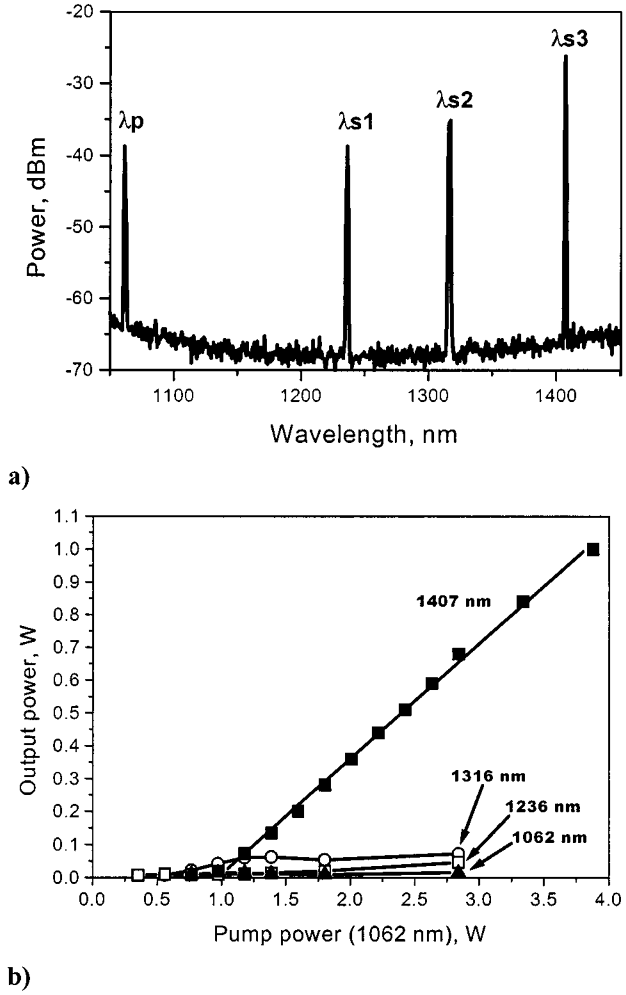

Fig. 10. Output characteristics of the 1407-nm Raman laser. (a) Spectrum of the output radiation. (b) Output power of the Raman laser versus the pump power of the Nd fiber laser.

improvement could be achieved by a substantial reduction of the excess losses in the fiber gratings. In that case, an output power of 1.5 W efficiency of 50% with respect to 1.06-μm radiation is achievable.

C. Raman Laser on the Base of Phosphosilicate Fibers Using the Stokes Frequency Shifts of 1330 and 490 cm^{-1} [29], [30]

The existence of two bands in the Raman gain spectrum of phosphosilicate fibers provide more possibilities to generate new laser wavelengths. With a tunable Yb double-clad fiber laser as a pump source, it is possible to get any wavelength in the very important for communication spectral region of 1.1–1.6 μm with not more than three cascades of Raman conversion.

Below we will describe a 1407- and 1430-nm Raman fiber lasers which can be used for pumping a 1500-nm Raman fiber amplifier and for medical applications correspondingly.

The scheme of these lasers is shown in Fig. 9.

As an active fiber of the 1407-nm laser, we used a specially developed P-doped silica fiber. The fiber length was 975 m. It is important that the active fiber had relatively low optical losses at the wavelength 1.4 μm connected with OH groups (1.1 dB/km). The Raman gain properties of a fiber can be characterized by means of the fiber Raman gain coefficient $\boldsymbol{g_0}$ (dimensionality of dB/km·W). This quantity may be considered as $\boldsymbol{g_0} = \boldsymbol{G_R}/\boldsymbol{A}_{\text{eff}}$, where $\boldsymbol{G_R}$ is the mean Raman gain coefficient of the core material (usually expressed in m/W) and $\boldsymbol{A}_{\text{eff}}$ is the effective area of the fiber core. But in contrast to $\boldsymbol{G_R}$ and $\boldsymbol{A}_{\text{eff}}$, $\boldsymbol{g_0}$ can be measured directly for each fiber under investigation (see e.g., [10], [27]).

The fiber Raman gain coefficient, measured for active fiber of the 1407-nm laser, turned out to be $\boldsymbol{g_0}$[1.3 μm/1.24 μm] $= 5.4$ dB/(km·W) (SiO_2-related Stokes) and $\boldsymbol{g_0}$[1.24 μm/1.06 μm] $=$ 6.8 dB/(km·W) (P_2O_5-related Stokes). The ratio of figures given in brackets is the ratio of signal and pump wavelength. The close values of these Raman gain coefficients enabled us to use the generation of both SiO_2- and P_2O_5-related Stokes components.

The RFL had three embedded optical cavities at the wavelengths $\lambda_{s1} = 1236$ nm, $\lambda_{s2} = 1316$ nm, and $\lambda_{s3} = 1407$ nm, at the three successive Stokes wavelengths. λ_{s1} corresponds to the P-associated Stokes shift of 1330 cm^{-1}, λ_{s2} and λ_{s3} to the SiO_2-associated Stokes shift of 490 cm^{-1}. So to attain the necessary wavelength of 1407 nm in an efficient cascaded Raman laser based on a single P-doped silica fiber, the successive generation of Stokes components associated with different constituents of the fiber core (P_2O_5 and SiO_2) was used. Cavities of the fiber lasers were formed by pairs of the FBGs, written in a germanosilicate fiber and spliced with the Nd-doped and P-doped fibers.

The output spectrum of the Raman laser is given in Fig. 10(a). The dependence of the output power at λ_{s3} on the pump power at λ_p is shown in Fig. 10(b). The bandwidth of the 1407-nm line is about 0.5 nm.

The laser slope efficiency of 35% was observed. This value may be considered high enough taking into account sharp dependence of the efficiency on the loss level in the Raman laser cavity. The higher loss level is explained by the specific generation wavelength ($\lambda = 1407$ nm) which coincides with a maximum of the OH absorption in the fiber. Curves ○, □, and ▲ [Fig. 10(b)] illustrate the output power at the wavelengths λ_{s2}, λ_{s1}, and λ_p, respectively.

The similar laser scheme was used to generate laser radiation at the wavelength of 1430 nm. Raman lasers operating at this wavelength are very promising for medical applications because there is a water absorption band with the peak wavelength equal to 1430 nm. To get this wavelength as a pump source we used a Yb DCFL operating at the wavelength of 1.089 nm. The output power at 1430 nm was 1.4 W.

III. Conclusion

A family of CW Raman fiber lasers pumped by Yb (Nd) double-clad fiber lasers has been developed.

Main characteristics of these lasers are as follows:

- spectral region of generation 1.1–1.6 μm;
- single-mode output power 1–10 W;
- spectral bandwidth of radiation ~1 nm;
- generation efficiency close to 50%.

Germanosilicate and phosphosilicate fibers have been used as an active medium. Phosphosilicate fibers have two strong Raman gain bands shifted from a pump radiation frequency by 490 and 1330 cm^{-1}. This permits to obtain practically any wavelength in the spectral region of 1.1–1.6 μm with a less number of Raman conversion cascades.

To get full advantage of phosphosilicate fibers as an active medium, it is necessary to further reduce optical losses of high phosphorus-doped fibers and improve the quality of in-FBGs.

At present the main application region of Raman fiber lasers is the pumping of Raman and Er-doped amplifiers.

Using higher power Yb (Nd) DCFL for pumping it is possible to obtain an output power of several tens W. Taking into consideration the high brightness and quality of output beams, and the possibility of choosing generation wavelengths, Raman fiber lasers can also find wide applications for material processing, printing, marking, medical and free space optical communication applications.

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