Laser-diode-pumped phosphosilicate-fiber Raman laser with an output power of 1 W at 1.48 μm

V. I. Karpov, E. M. Dianov, V. M. Paramonov, O. I. Medvedkov, M. M. Bubnov, S. L. Semyonov, S. A. Vasiliev, V. N. Protopopov, and O. N. Egorova

Fiber Optics Research Center at the General Physics Institute, Russian Academy of Sciences, 38 Vavilov Street, Moscow 117942, Russia

V. F. Hopin and A. N. Guryanov

Institute of High Purity Substances, Russian Academy of Sciences, Niznij Novgorod, Russia

M. P. Bachynski and W. R. L. Clements

MPB Technologies, Inc., 151 Hymus Boulevard, Pointe Claire, Quebec H9R 1E9, Canada

Received March 18, 1999

An all-fiber 1.48-μm generator based on a laser-diode-pumped Yb-doped double-clad laser and a cascaded Raman wavelength converter has been developed. Second-order Raman Stokes radiation was generated in a phosphosilicate-fiber resonator formed by two pairs of Bragg gratings. A slope efficiency of the Raman converter of 48% with respect to the power emitted by the double-clad Yb laser has been achieved. We obtained an output power of 1 W at a slope efficiency of 34% with respect to the laser-diode array power, with a total optical-to-optical efficiency of 23%. © 1999 Optical Society of America

OCIS codes: 060.0060, 190.5890, 140.3550, 140.3480, 350.2770.

Remote pumping of Er-doped fiber amplifiers requires high-output-power lasers emitting at 1.48 μm. Also, the power margin of long fiber links carrying 1.55-μm band signals can be increased by distributed Raman amplification when high-intensity light near 1.45 μm is launched into the transmission fiber. Sources with cw powers of ~500 mW in a single-mode fiber have been achieved through polarization and wavelength multiplexing of several laser diodes (LD's). Much higher output powers can be obtained in cascaded Raman fiber converters[1,2] pumped by LD-pumped double-clad lasers.[2] However, because of the small Raman frequency shift of 440–490 cm^{-1} in germanosilicate fibers, the radiation at 1.48 μm corresponds to the sixth Stokes order for pumping at 1.06 μm. On the other hand, phosphosilicate fiber[3] has a Stokes frequency shift of 1330 cm^{-1}, and 1.48-μm radiation corresponds to the second Stokes order for a 1.06-μm pump. The resultant reduction in the number of Bragg gratings greatly simplifies the scheme of the Raman converter and makes it more reliable. In Ref. 4, 1.24- and 1.48-μm phosphosilicate-fiber lasers pumped by a Nd:YAG laser were demonstrated. For field applications, LD-pumped devices are preferable. Recently we developed a 1.48-μm generator based on a LD-pumped Yb-doped double-clad fiber laser with a phosphosilicate-fiber Raman converter incorporated into its resonator.[5] However, the laser efficiency was restricted by considerable losses inside the fiber Raman resonator and by nonoptimal reflectivity of the output coupler.

In this Letter we present a 1.48-μm fiber laser with an output power of 1 W. We have considerably improved the laser efficiency by using a P-doped fiber with lower loss and reducing the splicing losses inside the laser resonator. To stabilize the feedback of the Yb laser at 1.06 μm, an additional fiber Bragg grating was inserted between the Yb fiber and the Raman converter.

Figure 1 shows the experimental setup, including a pigtailed LD array pump module (Opto Power Model OPC-D003-977-HP), an 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 a highly reflecting 1.06-μm Bragg grating written in the core. The output coupler was formed by a 5% Bragg grating. The estimated mode field diameters (MFD's) of the Yb fiber and the standard fiber at 1.06 μm were 6.9 and 7.1 μm, respectively, 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[6] was 13 m, long enough to absorb the pump radiation at 976 nm. 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

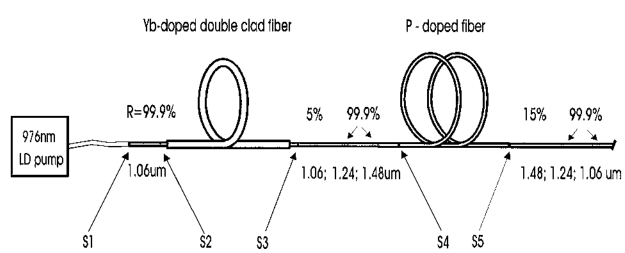

Fig. 1. Experimental setup of the 1.48-μm generator pumped by an Yb-doped double-clad fiber laser.

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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 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 ~13 mol. % of phosphorous, yielding a refractive-index difference of 0.011. The optical losses of the fiber length were 1.7, 1, and 0.8 dB at 1.06, 1.24, and 1.48 μm, respectively. The P_2O_5-doped fiber had MFD's of 6.3 and 10.4 μm at 1.06 and 1.48 μm, whereas the corresponding MFD's in the Flexcor fiber were 7.1 and 12.7 μm, respectively. In spite of the mismatched MFD's, by optimizing the splicing conditions we achieved an optical loss of only 0.05 dB when we spliced these fibers (splices S4 and S5).

Figure 2 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 relative amplified stimulated emission level inside the 1500–1570-nm band is −75 dB. The output power of the second-order phosphosilicate Stokes is shown in Fig. 3. The threshold for 1.24-μm radiation is ~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 ~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. The calculated ratio of output power to the length of the phosphosilicate fiber is shown in Fig. 4 for two values of excess loss. 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 improvement could be achieved by substantial reduction of the excess losses in the fiber gratings. In that case, an output power of 1.5 W is indicated, at an efficiency of 50% with respect to 1.06-μm radiation.

In conclusion, we have developed a 1.48-μm laser with an output power of 1 W, based on a LD-pumped Yb-doped double-clad fiber laser with a phosphosilicate-fiber resonant Raman converter. A 1.48-μm slope efficiency of 34% has been achieved. An output power of more than 1.5 W cw is predicted for reduced grating loss and optimum fiber length.

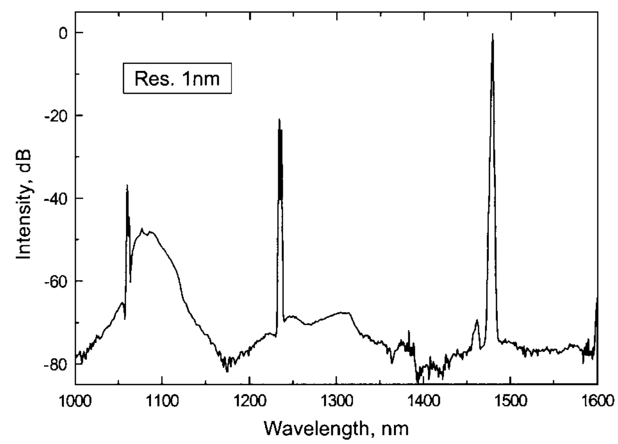

Fig. 2. Emission spectrum at the output of the Raman converter.

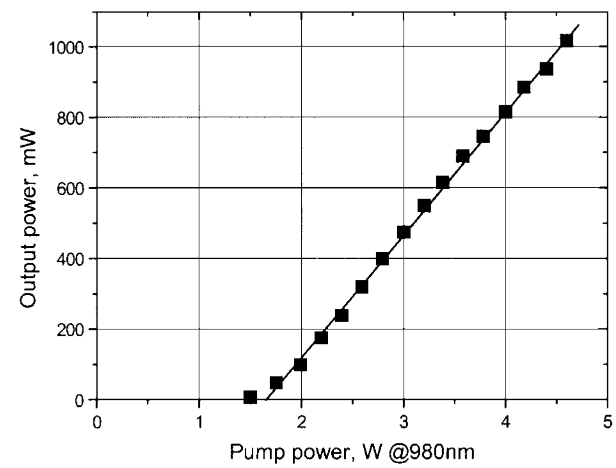

Fig. 3. Power of the second-order Stokes wave at the output of the Raman converter versus pump power.

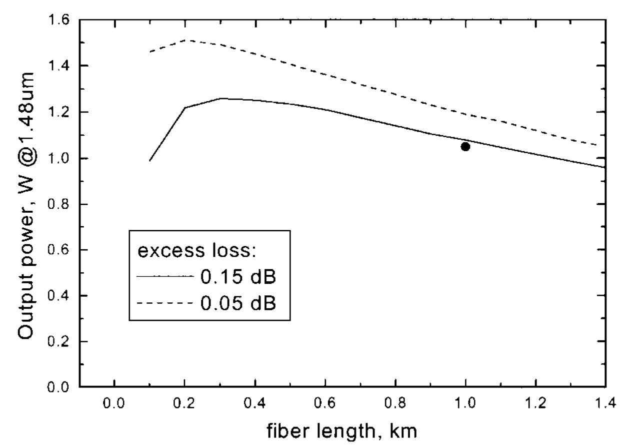

Fig. 4. Calculated output power of the 1.48-μm laser versus fiber length for two values of excess loss (pump power, 3 W at 1060 nm). Filled circle, experimental result.

The all-fiber design and the simple, two-step resonant Raman conversion scheme are advantages of the laser. High output power, a rather broad emission spectrum, and strong suppression of amplified spontaneous emission make this laser attractive for use in remote pumping of Er-doped fiber amplifiers.

The authors acknowledge design and fabrication of the Yb-doped double-clad fiber by A. S. Kurkov and A. Y. Laptev and thank I. A. Bufetov for fruitful discussions and for creating a simulation program. V. Karpov's e-mail address is karpov@fo.gpi.ac.ru.

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