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Fiber Raman Laser at 1450 nm for Medical Applications

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Abstract—Raman-fiber source emitting 1450 nm with a power of 1 W was realized. The application of the commercially available pump source with an output power of 35 W allows one to increase the output power up to 5 W. The emission wavelength corresponds to the water absorption band therefore it is promising laser for the surgery and other medical applications.

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INTRODUCTION

Fiber lasers are very attractive for medical applications due to their compactness, simplicity of the operation, service, etc. In many respects, the efficiency of the medical application is determined by the emission wavelength of the fiber laser. Some medical treatments require a large coefficient of the laser emission absorption. In this case, the laser emission spectrum should correspond to the tissue absorption bands given by water. One of the water absorption bands in the near-IR range is located around 1.45 μm. Then, there is an interest in creating a fiber laser emitting in this range for the surgery and therapy. However, fiber lasers based on a rare-earth doped fiber emit at wavelengths determined by optical transitions. Yb-doped fiber lasers operate in the range of 0.98–1.18 μm [1], while Er-doped lasers operate in the range of 1.53–1.60 μm [2]. The emission spectrum of an Ho-doped fiber laser also corresponds to the water absorption band near 2 μm; however, it has a high threshold of lasing [3]. Another way to build a fiber source for the required spectral range consists in the application of the Raman conversion. Raman fiber lasers pumped by Yb-doped fiber lasers allow one to achieve any wavelength within the near-IR range [4]. In this paper, we present one possible scheme for these lasers and compare the obtained results with the characteristics described in other works.

LASER DESIGN

Usually, Raman-fiber lasers are based on the two fiber types—phosphorsilicate (P doped) or germanosilicate (Ge doped). Figure 1 illustrates the normalized Raman gain spectra for both fiber types. Ge-doped fibers exhibit a gain peak near 440 cm^{-1} and P-doped fiber exhibit a peak at 1330 cm^{-1}. The application of a P-doped fiber allows one to minimize the number of conversion stages and to simplify the Raman laser scheme [5]. At the same time, Ge-doped fibers have smaller optical losses and a higher potential efficiency [6]. It should be noted that the wavelength of 1450 nm is "uncomfortable" for Raman lasers. The application of a Ge-doped fiber as the active medium requires four stages of conversion, which complicates the laser scheme. To get this wavelength using a two-stage converter based on P-doped fiber, it is necessary to start from 1049 nm where the efficiency of the Yb-doped fiber laser is small and the lasing is unstable. Therefore, to build a Raman-fiber laser, we have chosen the com-

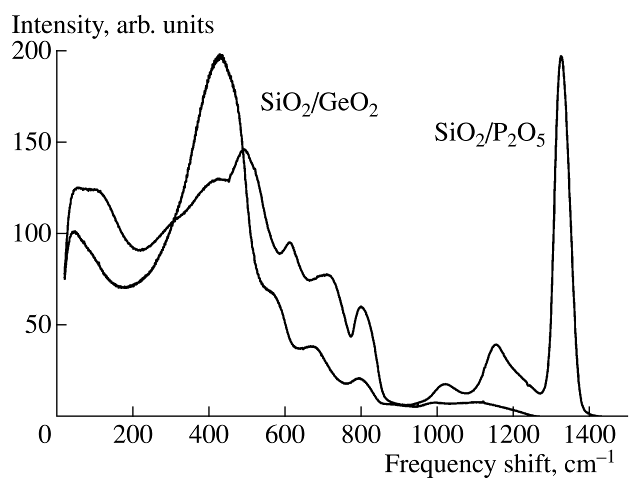

Fig. 1. Normalized Raman gain spectra for P-doped and Ge-doped fibers.

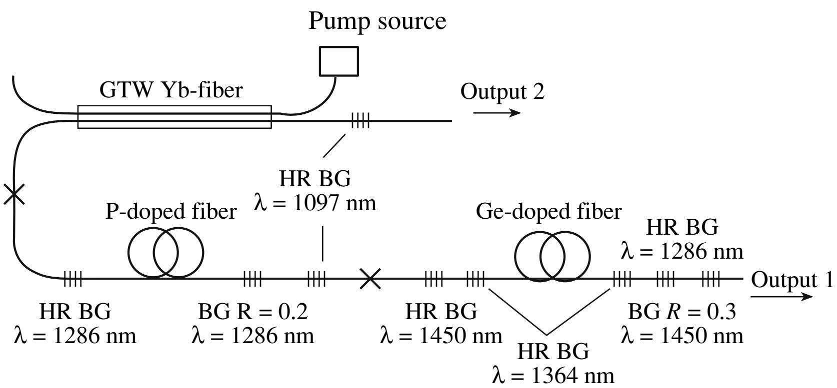

Fig. 2. Scheme of the composite Raman laser.

posite scheme, where the P-doped fiber was used to convert the fiber laser emission at 1097 nm to an emission at 1286 nm. The second stage, based on a standard telecommunication Ge-doped fiber, was used for the two-stage conversion from 1286 to 1450 nm. The laser scheme is shown in Fig. 2. To build the Yb-doped fiber laser, we have used a linear scheme based on the GT-wave fiber constituting a collection of the Yb-doped fiber and passive-multimode fiber in a general polymer coating with a refractive index lower than that for silica glass. In this design, the pump power is delivered through the passive fiber. This allows one to monitor the lasing from both ends of the active fiber. The laser cavity was closed by high-reflective (HR) Bragg gratings with the resonance at 1097 nm. The length of the P-doped fiber was 400 m, and the Ge-doped fiber was 1000 m long. The fiber parameters were similar to the characteristics described in [5, 6]. It should be noted that the application of the composite scheme allows one to monitor the quality of the device on the different stages of fabrication.

EXPERIMENTAL RESULTS

Curve *1* in Fig. 3 shows the power of the Yb-doped fiber laser without a converter versus the power of the semiconductor source. The maximum power of 5.9 W was achieved for the pump power of 10 W. The laser power from output 2 (through the Bragg grating) was several tens of mW. To convert the Yb-laser emission to that at 1286 nm, it was spliced with the converter based on a P-doped fiber. Curve *2* in Fig. 3 illustrates the power at 1286 nm versus the pump power, and curve *3* shows the remaining power of the Yb-doped fiber laser. One can see that the later presents a nonlinear dependency and the maximum remaining power at 1097 nm

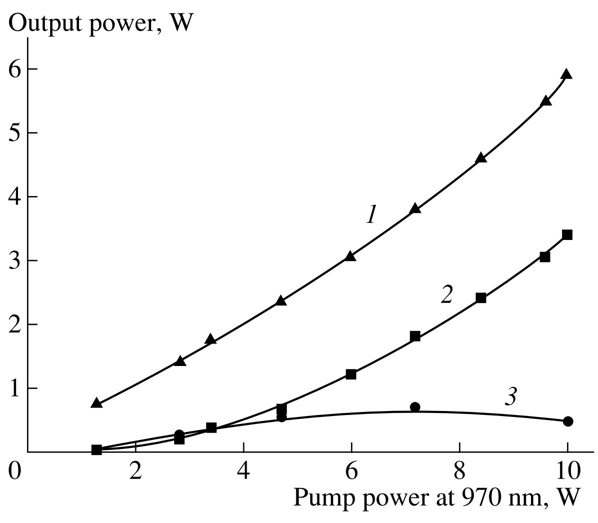

Fig. 3. Power of the Yb-doped fiber laser (*1*), the output power at 1286 nm (*2*), and the remaining power of the Yb-doped fiber laser (*3*) versus the pump power.

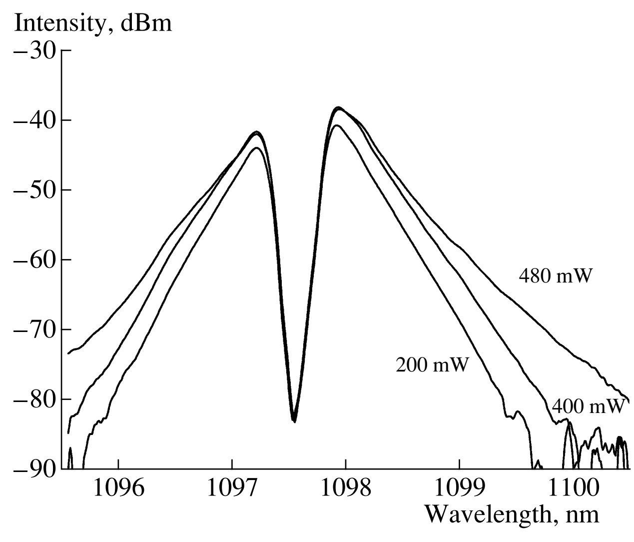

Fig. 4. Emission spectra from output 2 for different values of the power.

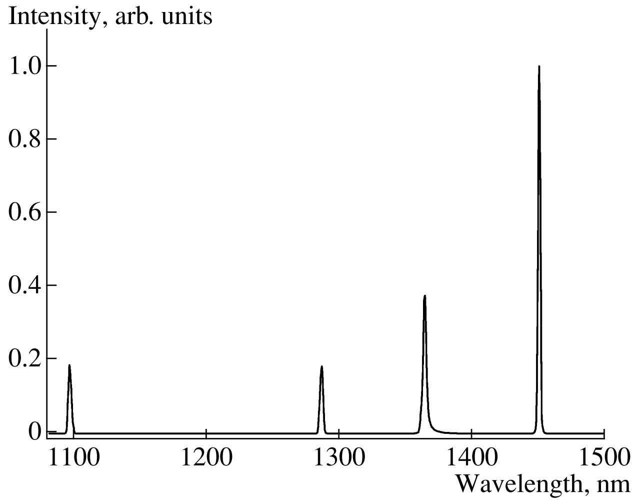

Fig. 5. Normalized output spectrum of the composite Raman laser.

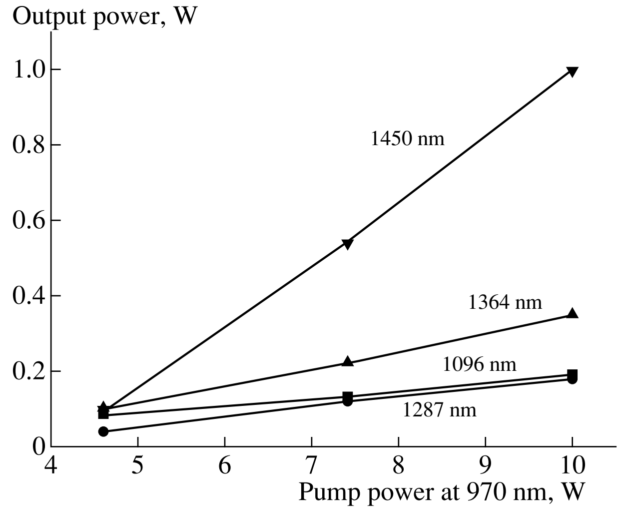

Fig. 6. Power at various spectral components versus the pump power.

is approximately 0.5 W. Emission monitoring from output 2 shows a growth in the backward power after the connection with the converter up to 0.48 W for the maximum pump power. Spectral measurements show that the main part of this power corresponds to the emission at 1097 nm. Figure 4 illustrates the emission spectra from output 2 for different values of power at this wavelength. The central dip corresponds to the reflection spectrum of the input Bragg grating centered at 1097 nm. The tails of the spectra correspond to the effect of the spectral overflow. Approximately, the same power at 1097 nm was observed from the opposite side of the laser. In fact, the spectral overflow leads to the loss of 1 W of power for the Yb laser, which decreases th conversion efficiency. Earlier, this phenomenon was described for the intermediate Stokes components of a multistage Raman laser [7]. Now, we have shown that it is essential for the Yb-laser emission as well as for the Stokes components.

The connection with the second stage based on a Ge-doped fiber allowed us to achieve the emission at 1450 nm. Figure 5 shows the normalized output spectrum of the entire device. One can see that the essential part of the output power is contained in the other spectral components. Figure 6 illustrates the power at various spectral components versus the pump power. The maximum output power at the final wavelength (1450 nm) is 1 W with a threshold of 4.5 W, which corresponds to an efficiency slope of 18%. The total power of the other components is 0.7 W. The same effect for the spectral overflow is responsible for this optical power.

COMPARISON OF DIFFERENT LASER DESIGNS

It should be noted that the emission in the range of 1450 nm can be achieved using another Raman laser design. As mentioned above, it consists in the use of a two-stage converter based on a P-doped fiber starting from the emission at 1049 nm provided by the Yb-doped fiber laser. The characteristics of this laser are indicated in the table (a). One can see that, in spite of a high efficiency for the conversion of the Yb-laser emission, the total efficiency (relative to the power of the semiconductor pump source) is not so high, because of a small lasing efficiency at 1049 nm. Another approach exploits the presence of a silica Raman component in the gain spectrum of a P-doped fiber. In this case, it is

Comparison of characteristics of Raman-fiber lasers with different designs

	Fiber type	Raman shifts used, cm^{-1}	Wavelength of the Yb-doped fiber laser, nm	Max. power of the Yb-doped fiber laser, W	Max. output power at 1.45 μm, W	Conversion efficiency (relative to Yb-laser)	Total efficiency (relative to pump power)
a	P-doped	1300 + 1300	1049	4.8	1.6	0.33	0.13
b	P-doped	1300 + 450 + 450	1089	6.8	1.1	0.16	0.09
c	Standard	4 × 450	1128	6.2	1.9	0.3	0.16
d	P-doped + standard	1300 + 450 + 450	1097	6	1	0.17	0.1

possible to make one conversion at 1300 cm^{-1} and two conversion stages at 450 cm^{-1} using one fiber [8]. The characteristics of this laser are shown in table (b). The conversion efficiency is essentially smaller than in the previous case. This can be explained by the increasing number of Raman conversions in the P-doped fiber having a high level of optical losses (more than 1 dB/km). Configuration (c) in the table corresponds to a four-stage conversion in the standard low-loss telecommunications fiber [9]. In this case, the highest efficiency was achieved. The parameters of the laser realized in this work are indicated as (d) in the table. One can conclude that the efficiency of this configuration is less than that for the configuration (a, c), while it is better than for scheme (b). We can believe that a loss in the efficiency can be explained by the application of the composite scheme with two separate cavities.

CONCLUSIONS

We have realized a Raman-fiber source emitting 1450 nm with a power of 1 W. We have used a composite scheme, where the P-doped fiber was used to shift the fiber-laser emission at 1330 cm^{-1}, and the standard telecommunications fiber was used for the two-stage conversion with the frequency shift of 450 cm^{-1}. The application of the commercially available pump source with an output power of 35 W allows one to increase the power up to 5 W. Then, this source can be studied for medical application.

The strong broadening of the Yb-laser spectrum after splicing with a Raman converter was observed. This decreases the source efficiency. A comparison with other Raman laser schemes shows disadvantages of the composite scheme through the division on two cavities.

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