High-power 1.48 µm phosphoro-silicate-fiber-based laser pumped by laser diodes

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High-power 1.48 μm phosphoro-silicate-fiber-based laser pumped by laser diodes

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Abstract: An all-fiber 1.48 μm generator based on a LD-pumped Yb-doped double-clad laser and 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. The Yb-doped double-clad fiber laser was pumped by seven laser diodes combined via a low-loss fused fiber coupler and provided 4.4 W at 1.06 μm at the input of the Raman converter. A slope efficiency of the Raman converter of 40% with respect to the power emitted by the double-clad Yb laser has been achieved. We obtained an output power of 1.5 W with a total optical-to-optical efficiency of 21%. It was found that four-wave mixing, initiated in the fiber by the high-intensity light, results in spectral broadening of the 1.48 μm radiation and leaking of the first-Stokes radiation from the resonator formed by the 1.24 μm Bragg gratings, thus reducing the efficiency of the first-to-second-Stokes conversion.

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Résumé : Nous avons développé une source toute fibre à 1.48 μm basée sur un laser à double couche dopé au Yb, avec pompage LD et convertisseur Raman. Nous avons généré de la radiation de Raman Stokes de deuxième ordre dans une source à fibre de phosphosilicate formée de deux paires de réseaux de Bragg. Ce laser dopé au Yb a été pompé par sept diodes lasers combinées via un coupleur à fibre à faible perte et fournissant 4.4 W à 1.06 μm à l'entrée du convertisseur Raman. Le taux d'efficacité du convertisseur a atteint 40%, donnant une puissance de sortie de 1.5 W, pour une efficacité optique–optique de 21%. Nous observons que le mélange à quatre ondes, initié dans la fibre par la haute intensité de la lumière génère un élargissement spectral de la lumière à 1.48 μm et une fuite de la première radiation de Stokes du résonateur formé des réseaux de Bragg à 1.24 μm, réduisant ainsi l'efficacité de conversion de première à deuxième radiation de Stokes.

[Traduit par la rédaction]

High-output-power lasers emitting in the spectral region of 1.43–1.48 μm are required for remote pumping of erbium-doped fiber amplifiers and distributed Raman amplification of optical signals in long-haul communications links. Sources with CW powers of $\sim$800 mW in a single-mode fiber have been achieved through polarization and wavelength multiplexing of several LDs [1]. Significantly higher output powers can be obtained more simply and cost-effectively in cascaded Raman fiber converters

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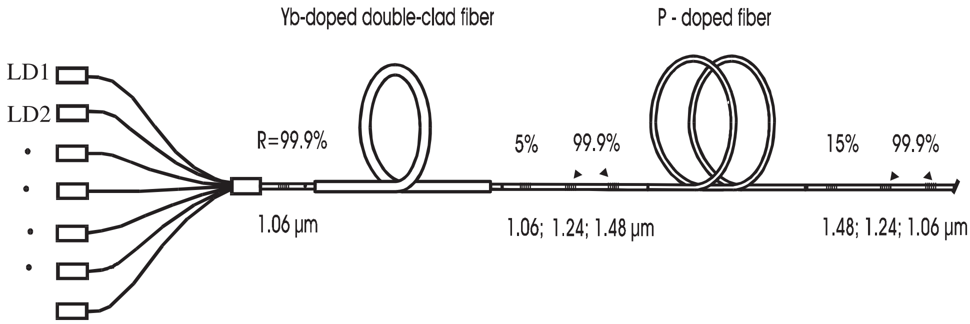
Fig. 1. Experimental set-up of the 1.48 μm generator pumped by Yb-doped double-clad fiber laser.



[2,3] pumped by LD-pumped double-clad lasers [3]. However, due to 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 when pumping at 1.06 μm. On the other hand, phosphosilicate fiber [4] 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 [5]. The resulting reduction in the number of Bragg gratings greatly simplifies the scheme of the Raman converter and makes it more reliable. Recently, we developed a 1.48 μm generator based on a phosphosilicate-fiber Raman converter and a Yb-doped double-clad fiber laser pumped by a LD array [6,7]. However, LD arrays do not have a sufficiently long lifetime to satisfy telecom reliability requirements. The recent introduction of telecom-qualified wide-stripe LDs with output powers of $\sim$1 W at 980 nm offers the possibility of telecom-grade Raman lasers based on the use of multiple LD pump modules. Moreover, a multi-LD pump configuration [8] provides “soft failure” protection in the event of the failure of one or even several of the laser diodes.

In this paper, we present a 1.48 μm Raman fiber laser with an output power of 1.5 W. The laser features a multipump architecture in which the combined output of seven LD modules is coupled into the inner cladding of an Yb-doped double-clad laser. The resulting high output power of the Yb laser allowed a substantial reduction (when compared to the results given in ref. 7) in the length of P-doped fiber required for the Raman converter, thus resulting in a significant cost benefit.

The experimental set-up is shown in Fig. 1. The pump light of seven 1 W laser diodes, pigtailed with 0.15 NA fiber and operating at 975 nm (Opto Power Corp.), is combined in a 7-to-1 fused optical coupler [9] and launched into the first cladding of the Yb fiber through the cladding of a 2.5 cm long piece of standard fiber (Flexcor 1060) with a highly reflecting 1.06 μm Bragg grating written in the core. The 7-to-1 coupler is formed by fusing seven individual fibers having an NA of 0.15 and then tapering the fused region down to approximately match the diameter of the Flexcor fiber. The wave-guide parameters and core composition of the Yb-doped fiber were similar to those described in ref. 10 except for a higher inner-to-outer-cladding numerical aperture. The fiber was coated by a low-index fluoropolymer giving an NA of 0.6. The pump combiner has an insertion loss of 8–10% in each pump channel, resulting in an input of 6.3 W at 975 nm into the inner cladding of the Yb fiber. The output coupler of the Yb laser was formed by a 5% Bragg grating.

The 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 hydrogen preloading and have the same parameters as in ref. 7 except for the output-coupler grating which, in this case, has a reflectivity of 33% at 1.48 μm and a bandwidth (FWHM) of 0.15 nm. The phosphosilicate fiber was 600 m long. The fiber core contains $\sim$13 mol% of phosphorous, giving a refractive index difference of 0.011. The optical losses of the 600 m of P-doped fiber were 1.5, 0.9, and 0.8 dB at 1.06, 1.24, and 1.48 μm, respectively.

Fig. 2. Output power of the 1.06 μm laser vs. LD pump power coupled into the inner cladding of the Yb fiber.

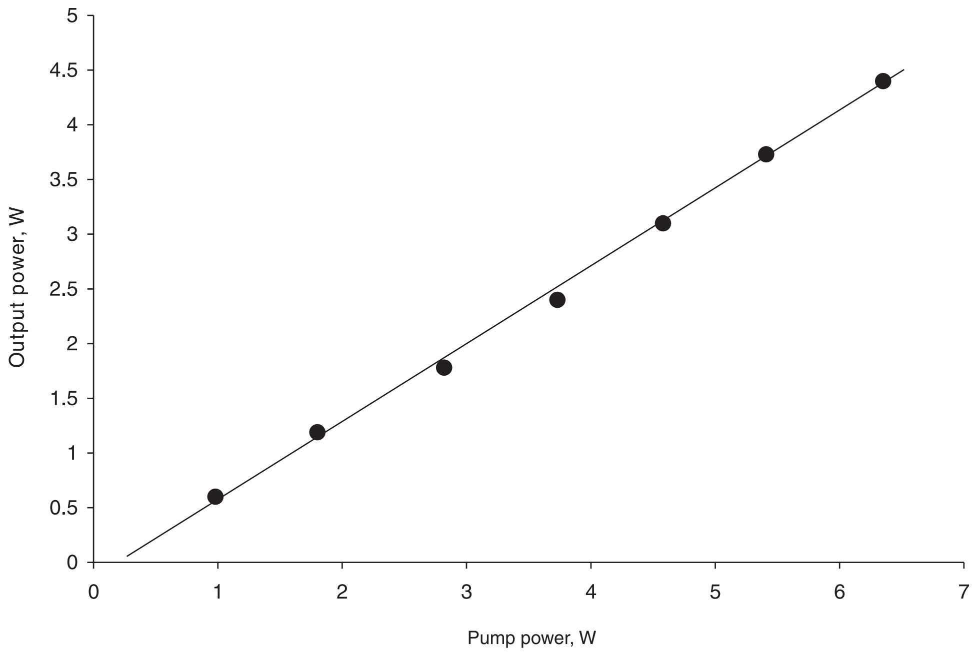


Fig. 3. Emission spectrum at the output of the Raman converter.

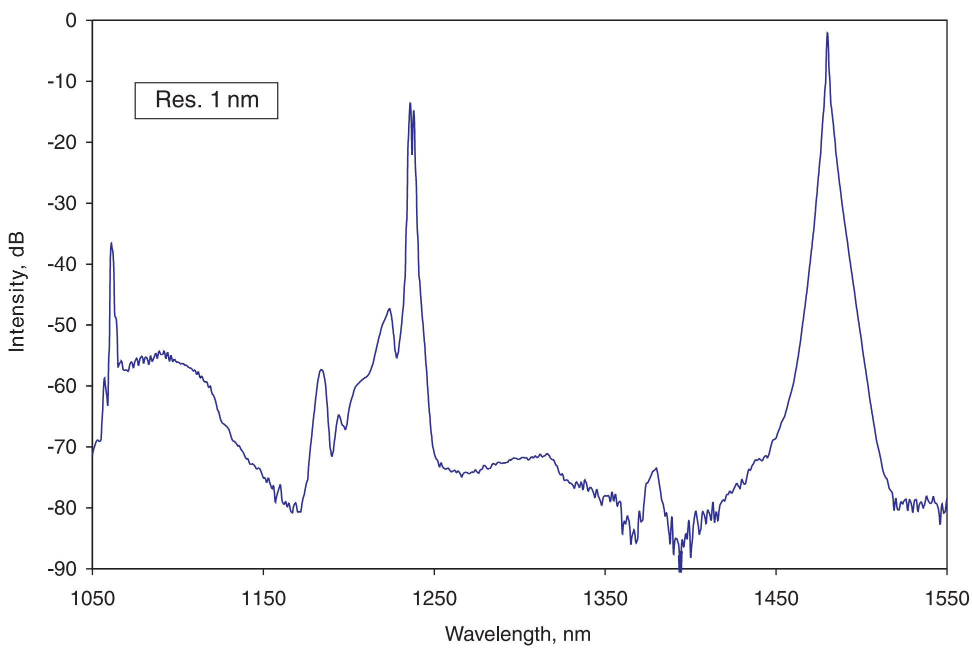


Fig. 4. First- and second-Stokes output powers vs. 1.06 μm pump power.

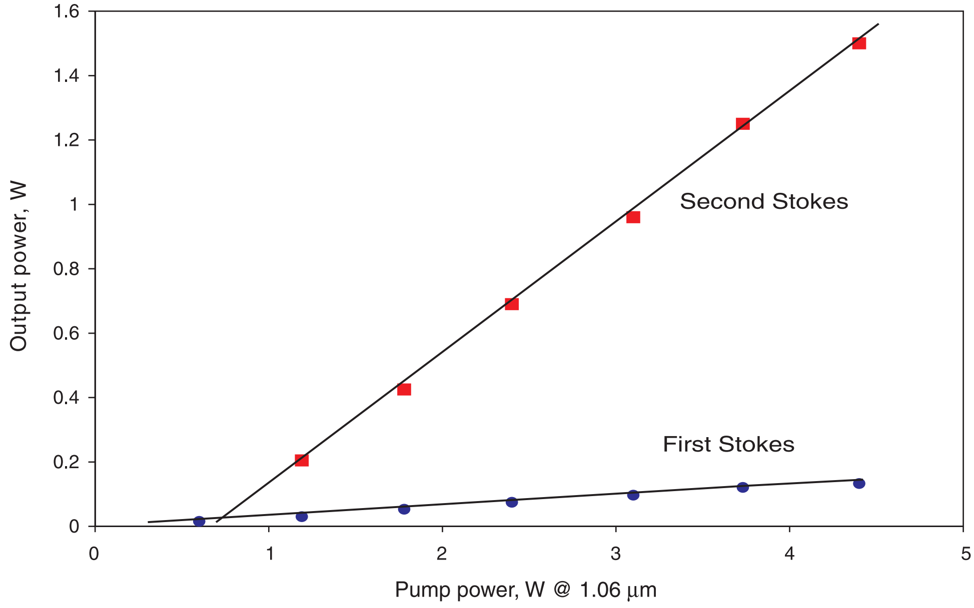
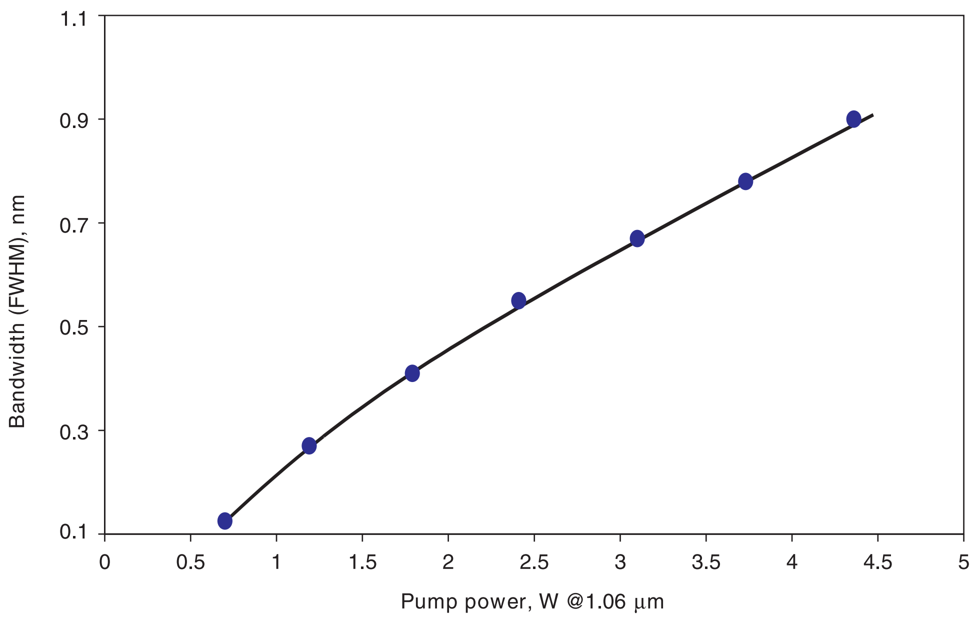
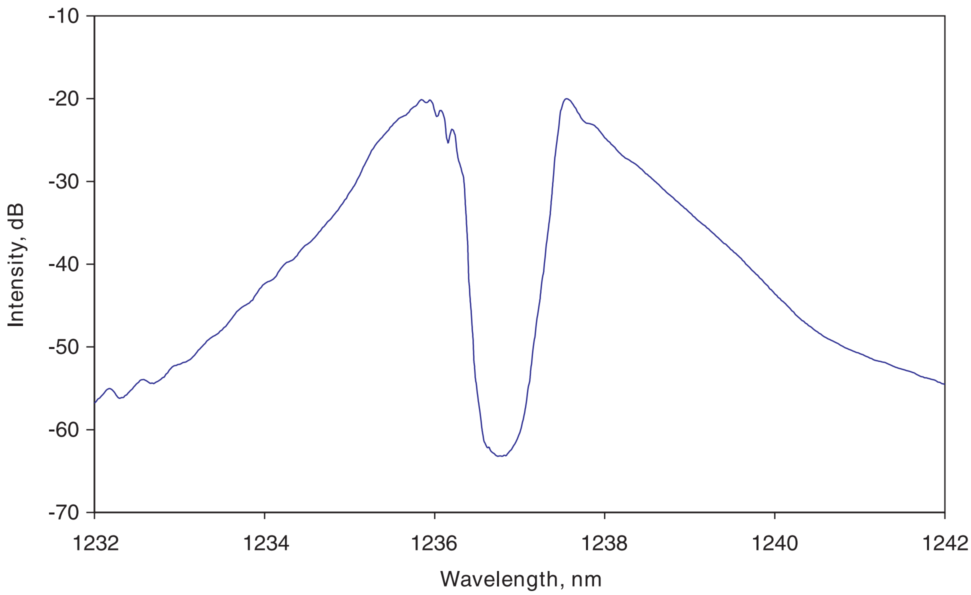


Fig. 5. Emission bandwidth (FWHM) of the 1.48 μm Raman laser vs. pump power.



The output of the Yb laser at 1.06 μm versus the pump power at the input of the Yb fiber is shown in Fig. 2. The multimode pump is transformed into high-brightness 1.06 μm radiation with a slope

Fig. 6. Spectrum of the first Raman Stokes emission.



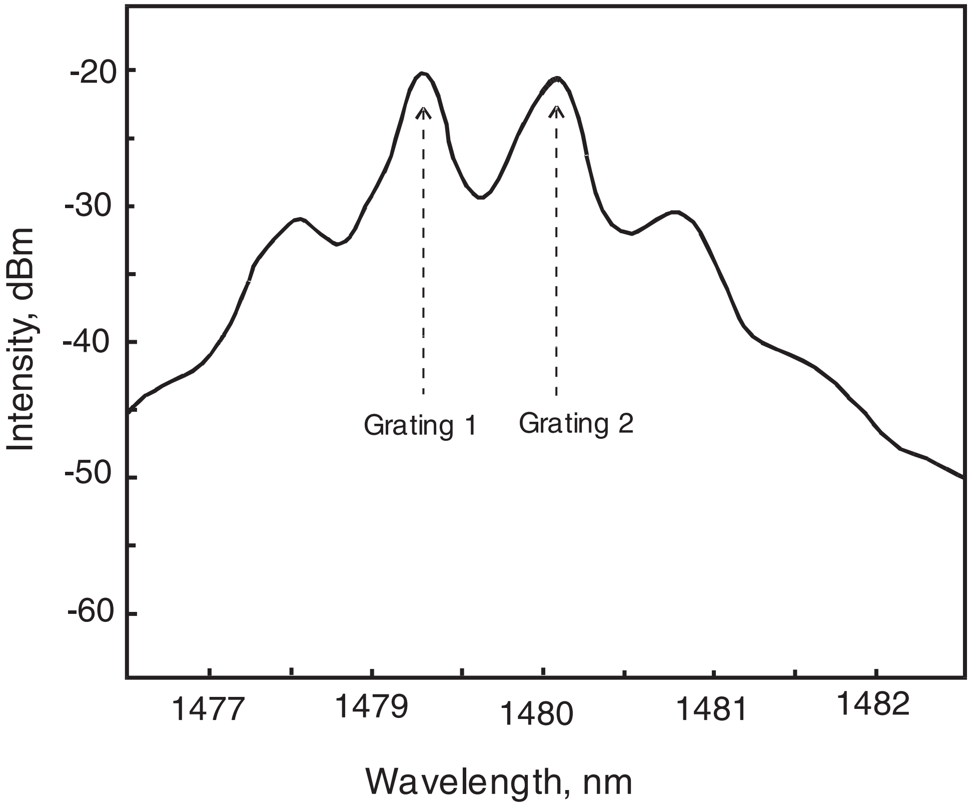
efficiency of 73%. The laser emits 4.4 W at a total LD pump power of 7 W, corresponding to a total light-to-light efficiency of 63%.

The emission spectrum measured at the output of the Raman laser when the total output power was 1.63 W is shown in Fig. 3. The suppression of the 1.24 μm radiation, corresponding to the first Stokes order of phosphorus, is 11 dB. The first- and second-order phosphosilicate Stokes output power versus the pump power of the Yb laser is shown in Fig. 4. The thresholds for the 1.24 and 1.48 μm radiation are approximately 0.3 and 0.7 W, respectively. As can be seen, the 1.24 μm output continued to increase with increasing pump power. At power levels higher than the threshold for second-Stokes generation, the first-Stokes power did not saturate as was observed in ref. 7. The slope efficiency of the 1.48 μm radiation with respect to the power at 1.06 μm is 40%. An output power of 1.5 W is reached at a 1.06 μm power of 4.4 W. As shown in Fig. 5, the spectral width of the 1.48 μm radiation increased with increasing pump power and, at the maximum power, reached a FWHM of 0.9 nm, a value which is considerably higher than the reflection bandwidth of the output coupler. The spectrum of the first-Stokes emission is shown in Fig. 6. The strong dip at the center of the emission is due to the output Bragg grating that has a reflectivity of more than 99.9%. Radiation within the grating bandwidth is, effectively, trapped inside the resonator. However, as can be seen from Fig. 6, there are spectral components that "leak" from both sides of the resonator grating. It was also clearly observed that the spectral width of the first-Stokes emission increased with increasing pump power.

The most probable cause of this spectral broadening is four-wave mixing (FWM) via the third-order nonlinearity. In this case, FWM and Raman processes are "cooperating," i.e., broad-band Raman spontaneous noise is amplified parametrically and stimulated Raman scattering contributes to amplification of the FWM signal and idler waves. Moreover, there are three FWM processes that can take place simultaneously, two that are quasi-degenerate and originate solely from 1.24 or 1.48 μm Raman Stokes waves, and a nondegenerate one that is caused by 1.24 and 1.48 μm pumps.

The parametric spectral broadening and the gain depend on all four nonlinear processes, the first- and second-Stokes intracavity intensities and the dispersion properties of the particular P-doped fiber

Fig. 7. Emission spectrum at the output of the Raman laser with two output Bragg gratings having reflection peaks separated by 0.85 nm.



(that, at present, are not very well known). It is, therefore, difficult to estimate the extent of the broadening to be expected as a result of FWM. Efforts to model the complex interaction between the Raman and FWM processes are in progress.

To demonstrate the FWM origin of the second-Stokes spectral broadening, an additional output Bragg grating, with its reflection peak shifted by 0.85 nm with respect to the peak of main output coupler, was spliced to the end of the optical train. The resulting output spectrum of the Raman laser (Fig. 7) clearly shows side bands shifted by $\pm$0.85 nm with respect to the two Bragg-grating reflection peaks.

From a practical point of view, the FWM spectral broadening increases intracavity losses due to the leakage of 1.24 and 1.48 μm light from both ends of the respective cavities. It is also responsible for the fact that the first-Stokes power does not saturate at pump power levels above the threshold for second-Stokes generation (Fig. 4). Reducing this leakage, especially in the first-Stokes cavity, through the use of broader Bragg gratings, should lead to an improvement in the Raman laser efficiency.

In conclusion, we have developed a 1.48 μm laser with an output power of 1.5 W, based on a LD-pumped Yb-doped double-clad fiber laser with a phosphosilicate-fiber resonant Raman converter. Key features of the laser include an all-fiber design; a multipump architecture based on reliable 1 W laser diodes; a low-loss pump combiner; and a simple, two-step resonant Raman conversion scheme. The high output power and relatively broad emission spectrum make it very attractive for remote pumping of EDFAs and distributed Raman amplification. Four-wave mixing, initiated by the high-intensity light circulating inside the Raman resonator, is thought to cause the observed spectral broadening and a resulting reduction in the efficiency of the first-to-second-Stokes conversion.

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