Neodymium-Doped Cladding-Pumped Aluminosilicate Fiber Laser Tunable in the 0.9-μm Wavelength Range

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***Abstract*—A tunable high-power cladding-pumped neodymium-doped aluminosilicate fiber laser is demonstrated. The maximum power reached was 2.4 W with a slope efficiency of 41% and a threshold pump power of 1.68 W, both with respect to launched pump power, when cladding pumped by two 808-nm diode pump sources at both fiber ends. The dependence of the tuning range on the fiber length is investigated. The tuning range changed from 922 to 942 nm for a 25-m-long fiber to 908–938 nm with a 14-m-long fiber, because of reabsorption effects. The output linewidth was 0.26 nm in a diffraction-limited beam. Operation on the challenging 0.9-μm three-level transition in neodymium-doped double-clad fiber laser was facilitated by a W-type core refractive index profile. This filtered out the unwanted and competing strong transition at 1.06 μm while guidance of 0.9 μm remained intact.**

***Index Terms*—Neodymium, optical fiber lasers, waveguide filters.**

I. Introduction

NEODYMIUM-DOPED fibers have been front runners in the development of fiber lasers since the very beginning due to the excellent spectroscopic characteristics and high optical efficiency. Thus, the first fiber laser [1], the first single-mode fiber laser [2], and the first cladding-pumped fiber laser [3] were all Nd-doped. Most of the research activity was focused on the relatively strong emission band at 1.06–1.09 μm ($^4F_{3/2} \rightarrow ^4 I_{11/2}$). With conventional 808-nm pumping, this corresponds to a four-level laser scheme. There is also a 0.9-μm transition which terminates on the ground level ($^4F_{3/2} \rightarrow ^4 I_{9/2}$). The three-level nature and associated ground-state absorption (GSA) makes it rather difficult to make lasers with this transition. Still, with traditional core-pumping, it is relatively easy to excite a sufficient fraction of the Nd ions to achieve gain on the 0.9-μm transition. Published results include a 42-mW core-pumped fiber laser tunable from 892 to 936 nm [4]. While the 1.1-μm gain will still exceed the 0.9-μm gain in most cases, the difference can be small enough to be reversed with wavelength-selective end-reflectors in case of core pumping. However, because of the low power of suitable pump sources, the powers that can be reached with core pumping are rather low. Cladding pumping is the preferred approach for power scaling of fiber lasers, and many potential applications would benefit from the higher powers that cladding pumping could enable. This includes single-mode sources for core pumping of ytterbium-doped active fiber devices [5], water sensing [6], and frequency doubling to the data storage wavelength of 458 nm in the blue [7]. However, cladding pumping of three-level transitions is difficult: Although the power from appropriate multimode pump sources is high, the intensity is relatively low, which makes it difficult to excite a sufficient fraction of Nd ions. The pump saturation intensity at which 50% of the Nd ions are excited is approximately $25 \text{ kW/cm}^2 = 0.25 \text{ mW}/\mu\text{m}^2$, which corresponds to a power of $\sim$ 2 W in a fiber with a 100-μm-diameter inner cladding diameter. We would however typically operate on the long wavelength side of the emission peak, where the emission cross-section is larger than the absorption cross section. Because of this quasifour-level characteristic, it is sufficient to excite, say, 10–20% of the ions rather than 50% to reach gain and threshold inversion. On the other hand, efficient pumping of an extended fiber implies that the pump power must be high enough to produce gain even after a significant fraction of it has been absorbed. Thus, several watts of pump power is required for efficient cladding pumping of a 0.9 μm Nd-doped fiber laser (NDFL) with a 100-μm inner cladding diameter. Currently available pump sources can fulfill this, but there is still another obstacle: The low overlap between the pump beam in the inner cladding and the Nd-doped core means that long fibers are required to absorb the pump. This compounds the problem with GSA, in that the competing four-level gain at $\sim$1.06–1.09 μm can reach unacceptably large values before the GSA at the three-level transition is overcome. Therefore, the emission at $\sim$1.06–1.09 μm must be suppressed in an efficient cladding-pumped 0.9 μm neodymium-doped fiber laser. Several approaches have been demonstrated, often in combination.

One option is to reduce the GSA. At low temperatures, the reduced thermal population of the Stark sublevels that the transition terminates on enables a neodymium-doped fiber to act as a four-level system at 0.9 μm when cooled to liquid nitrogen temperatures. Recently, a cladding-pumped

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nitrogen-cooled high-power 938-nm amplifier was demonstrated [8]. However, liquid nitrogen is impractical for most applications. Another option is to use a fiber host composition such as germanosilicate with favorable spectroscopy even at room temperature [9]. Results with this approach were recently published [10]. For suppression of the competing four-level emission (at $\sim$ 1.09 μm in a germanosilicate host) one can use a small inner-cladding-to-core-area ratio that allows the pump to be absorbed in shorter fibers with less GSA [11]. However, if the core size is enlarged to achieve this, then the fiber eventually becomes multimoded, which is normally undesired. Yet another approach is to use a filter that rejects four-level 1.06–1.09-μm emission. The filter must be distributed along the fiber, since the gain within the fiber is so high that strong amplified emission and/or spurious lasing will otherwise effectively clamp the population inversion in the fiber and thus prevent 0.9-μm lasing. A fiber with a W-type core refractive index profile can provide the required filtering, and is the method used in this paper. Such W-profile cores were studied thoroughly in the 1970s [12], mostly for dispersion compensation purposes. However, it is also well known that a W-profile core can act as a low-pass filter since even the fundamental P_{01} mode can have a nonzero cutoff [13]. This is in contrast to conventional step-index cores. W-profile cores have been used with germanosilicate neodymium-doped fibers, then allowing a smaller, single-mode, core to be used [14]. However, because of quenching, the maximum neodymium concentration in germanosilicate is limited to 0.1% by weight [9], and in particular with small cores, this leads to undesirably long fibers in which background loss can degrade the performance significantly. Thus, while a W-profile core allows a small, single-mode core to be used, the low permissible Nd-concentration can lead to a low efficiency in a germanosilicate host. Instead, one can use an aluminosilicate host, which allows for higher neodymium concentrations. On the other hand, the spectroscopy is less favorable, but with a W-profile core with good enough rejection of four-level emission (at $\sim$ 1.06 μm in a germanosilicate host), 0.9-μm operation is still possible, and higher efficiencies have been obtained than with germanosilicate neodymium-doped fibers. [15], [16]. Differences in spectroscopy also mean that aluminosilicate neodymium-doped fiber lasers typically emit at shorter wavelengths than germanosilicate neodymium-doped fiber lasers do.

In this paper, we investigate the spectroscopic and tuning characteristics of an aluminosilicate neodymium-doped fiber laser tunable in the 0.9-μm wavelength range. The wavelength-dependence of the waveguide filter and of the ground-state absorption lead to complex spectral characteristics, which combined with the requirements of different applications for different specific wavelengths and the potential of broadband tuning of a glass host gain medium, makes this investigation all the more interesting. A W-profile core was used to suppress guidance, and hence stimulated emission, at 1.06 μm. The laser was tunable from 922 to 942 nm when a longer fiber was used and from 908 to 938 nm when a shorter fiber was used. The maximum output power reached 2.4 W with a slope efficiency of 41% and a threshold pump power of 1.68 W, both with respect to launched pump power. The core was strictly single mode and the output beam was diffraction limited. This paper is organized as follows: Section II describes the design of the fiber and includes the spectroscopy of the Nd-doped aluminosilicate fiber. Section III presents the details and results of the fiber laser experiments. Brief conclusions are given in Section IV.

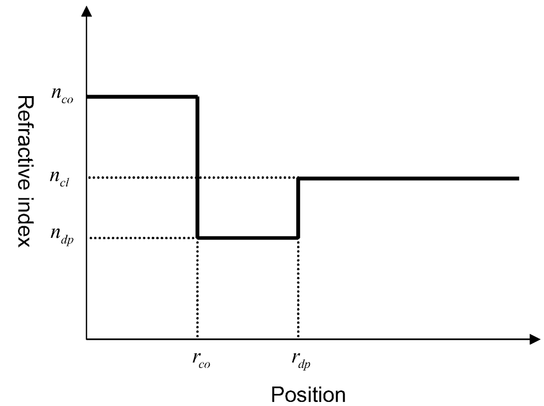

Fig. 1. Schematic diagram of a W-type core refractive index profile.

II. Fiber Design

In order to suppress undesired 1.06-μm emission, a careful design of the W-profile is needed to suppress the guidance at this wavelength. When the 1.06-μm emission is no longer guided, its overlap with the doped core is small. This reduces the amount of stimulated emission from excited Nd-ions. Next, we review the characteristics of a W-profile core, as described in [13]. Consider then a W-type refractive index profile according to Fig. 1, with raised core refractive index $n_{\rm co}$, depressed (first cladding) refractive index $n_{\rm dp}$, and second cladding refractive index $n_{\rm cl}$. (Note that in cladding-pumping terminology, the first and second cladding would constitute the inner cladding.) The core radius is $r_{\rm co}$, and the outer radius of the depressed region is $r_{\rm dp}$. Then, assuming weakly guiding condition and linearly polarized (LP) modes, the radial dependence of the transversal field component becomes [13]

$$\psi(r) = \begin{cases} A_0 J_m\left(u\frac{r}{r_{\rm co}}\right), & r \le r_{\rm co} \\ A_1 I_m\left(w'\frac{r}{r_{\rm dp}}\right) + A_2 K_m\left(w'\frac{r}{r_{\rm dp}}\right) & r_{\rm co} \le r \le r_{\rm dp} \\ A_3 K_m\left(w\frac{r}{r_{\rm dp}}\right), & r \ge r_{\rm dp} \end{cases} \quad (1)$$

where r is the radial position, $A_i (i = 0,1,2,3)$ is a constant, and J_m, K_m, I_m are Bessel functions, modified Bessel functions of the first kind, and modified Bessel functions of the second kind, respectively. The mode parameters are defined conventionally as $u = r_{\rm co}\sqrt{k_0^2 n_{\rm co}^2 - \beta^2}, w = r_{\rm dp}\sqrt{\beta^2 - k_0^2 n_{\rm cl}^2}$, and $w' = r_{\rm dp}\sqrt{\beta^2 - k_0^2 n_{\rm dp}^2}$, where β is the propagation constant of the mode and k_0 is the vacuum wave number. We can define a modal effective index $n_{\rm eff}$ by $n_{\rm eff} = \beta/k_0$. According to the boundary condition, the field and its radial derivative are

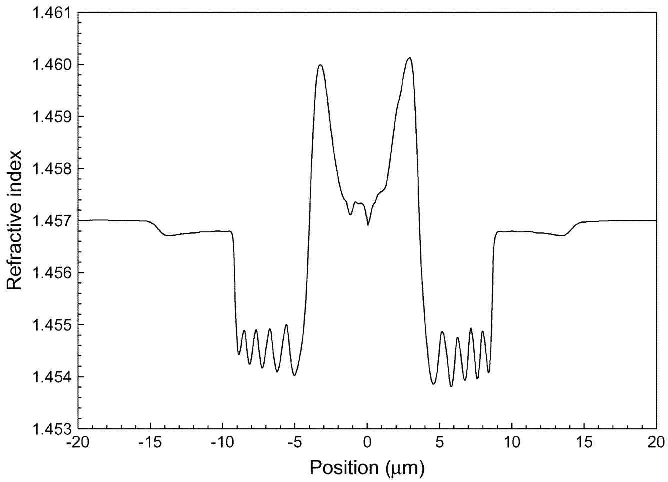

Fig. 2. Measured refractive index profile for W-type fiber used in the experiments.

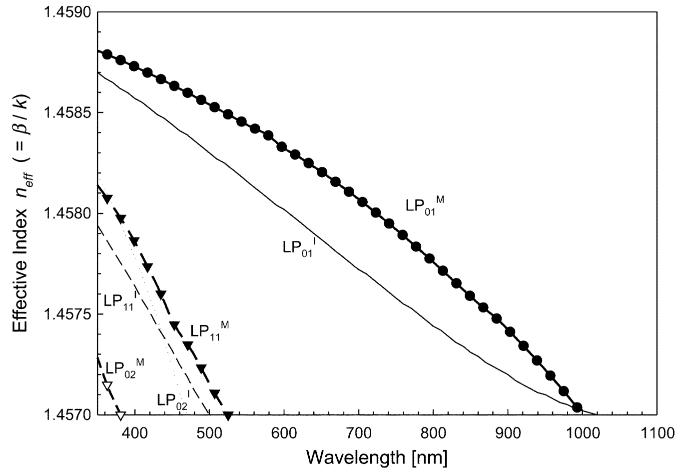

Fig. 3. Core guiding characteristics of a W-type refractive index fiber. Effective refractive indices for idealized refractive index profile (lines superscripted with "I") and those for measured refractive index profile (connected dots superscripted with "M").

continuous on the two boundaries, $r = r_{\rm co}$ and $r = r_{\rm dp}$. This condition leads to the characteristic equation as follows [13]:

$$\frac{\left[\hat{J}_m(u) - \hat{K}_m(w'c)\right]\left[\hat{K}_m(w) + \hat{I}_m(w')\right]}{\left[\hat{J}_m(u) + \hat{I}_m(w'c)\right]\left[\hat{K}_m(w) - \hat{K}_m(w')\right]} = \frac{I_{m+1}(w'c)K_{m+1}(w')}{I_{m+1}(w')K_{m+1}(w'c)} \quad (2)$$

where $\hat{Z}_m(x) = \frac{Z_m(x)}{xZ_{m+1}(x)}$ (Z represents Bessel functions) and $c = \frac{r_{\rm co}}{r_{\rm dp}}$.

All the mode parameters are functions of the propagation constant β, so (2) can be solved numerically for the quantized propagation constant β. Then the mode parameters u, w, w' as well as the mode profiles can be readily computed. Here, however, we are primarily interested in whether the P_{01} mode has a (positive) cutoff wavelength. It can be shown [13] that this is the case when

$$\frac{r_{\rm dp}}{r_{\rm co}} > \sqrt{\frac{\Delta n_{\rm co}}{|\Delta n_{\rm dp}|}} \quad (3)$$

where $\Delta n_{\rm dp} = n_{\rm dp} - n_{\rm cl}$ and $\Delta n_{\rm co} = n_{\rm co} - n_{\rm cl}$.

We fabricated a neodymium-doped fiber with a W-type core refractive index profile. The refractive index profile was measured and is shown in Fig. 2. The diameter of the second cladding was 100 μm. The fiber had a low-index polymer coating that acted as an outer cladding and enabled pump waveguiding within the glass fiber structure (core and first and second claddings), with a nominal NA of 0.49. We evaluated the average refractive index in the core $n_{\rm co}$ to 1.4590 and the average refractive index of the depressed region $n_{\rm dp}$ to 1.4546. Thus, we approximated the actual refractive index profile with an ideal W-profile. The core radius $r_{\rm co}$ was 3.5 μm and the outer radius of the depressed region $r_{\rm dp}$ was 8.7 μm. Fig. 3 shows numerical solutions of the propagation constant β, or equivalently, the effective refractive index $n_{\rm eff}$, of LP modes using the characteristic equation in (2) for a fiber with our idealized parameters (lines, labeled with superscript "I"). The fundamental P_{01} mode is cut off from 1 μm and above, meaning that the core does not guide light at wavelengths above 1 μm. The core supports a single mode from 0.5 to 1 μm. Interestingly, the effective index of the P_{02} mode is higher than that of the P_{11} modes for wavelengths below 400 nm as pointed out in [13].

However, the measured refractive index profile, shown in Fig. 2, indicates a large deviation from the idealized index profile in Fig. 1. In order to see the effect of nonidealized W-type profile, which has a large dip in the middle as shown in Fig. 2, we calculated the effective indices of guided modes based on the measured refractive index profile shown in Fig. 2. For this, we employed a mode solver for circularly symmetric structures with arbitrary index profile. It was based on the weakly guiding one-dimensional Helmholtz equation as in [17]. For the calculation, the measured refractive index profile was sampled into 50 points. For comparison, Fig. 3 shows the modal effective indices for the measured refractive index profile (lines with symbols, labeled with superscript "M"), in addition to those of the idealized index profile.

Beside the similar waveguide filter cut-offs ($\sim$1 μm), two things are noticed. Firstly, the P_{02}-mode cutoff of the measured refractive index profile occurs at much shorter wavelength than that of the idealized refractive index profile, due to the dip in the middle. Secondly, the effective index of the fundamental P_{01} is larger than with the idealized index profile for the laser wavelengths (908–942 nm). This suggests that the measured profile reduces the sensitivity to bending losses.

In order to compare the bending losses for those different index profiles, we used a commercially available software ("Fiber" provided by "TELMAC"). When the fiber bending diameter was 33 cm, as used experimentally, the P_{01} mode bending losses of the idealized index profile at 908 and 942 nm were calculated as 0.003 and 0.19 dB/m, respectively, while those of measured index profile were 0.0006 and 0.03 dB/m. From this, we predict that the wavelength dependent waveguide filter which we fabricated will in fact not show any significant wavelength dependent waveguiding loss within the laser tuning wavelength range.

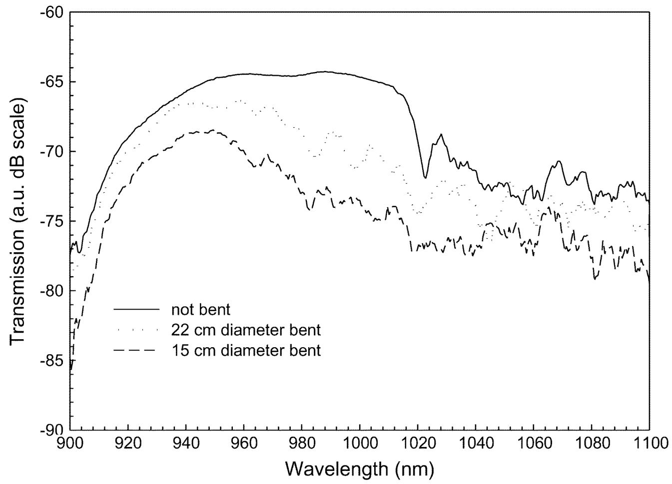

Fig. 4. Core transmission characteristics of W-profile NDF used in the experiments. The bent section was 1-m long.

Fig. 4 shows a measured core transmission spectrum through a 1-m-long piece of our fiber. This confirms that the core does not guide wavelengths over 1 μm while guidance is good below 1 μm. Hence, it is clearly shown that our designed W-type fiber has cut off at 1 μm. We also measured the bending loss characteristics with different bending radius. Since the fiber transmission characteristic is sensitive to bending loss, one can induce a wavelength-dependent bending loss that shifts the effective cutoff to shorter wavelengths, and possibly improves the suppression at 1.06 μm without incurring any penalty at 0.9 μm. From Fig. 4, it seems that the 33-cm bend diameter used experimentally did improve the suppression at 1060 nm. On the other hand, filtering loss appears negligible over the laser emission range up to 942 nm.

However, suppressing 1.06 μm is not enough to achieve efficient high-power 0.9-μm oscillation. It is also necessary to launch enough pump power so that the pump intensity is sufficient to reach population inversion, even after absorbing most of the pump power. Otherwise, it would not be possible to operate the laser with a high pump absorption, as is required for efficient operation. For the pump power and pump intensity, we rely primarily on the availability of high-power, high-brightness, pump sources.

Pump absorption can be a problem, as well, if it is low compared to background losses. This can be the case in a fiber with a core diameter as small as 7 μm, in particular in neodymium-doped fibers which are relatively susceptible to concentration-quenching. We shaped our fiber to a doubly truncated cross section, as is shown in Fig. 5. It is well known that a doubly-truncated or a singly-truncated cladding geometry enhances the pump absorption significantly, by eliminating cladding modes with poor overlap with the core [18]. Using this method, we succeeded to increase the pump absorption in the cladding from 0.5 to 0.8 dB/m when measured with a fiber length of 14 m, which is the shortest fiber used in the laser experiments. The truncation does however come at a price. The inner cladding becomes smaller, by 19% in this case. This by itself increases the pump absorption by reducing the inner-cladding-to-core area ratio. We estimate that this effect explains one third of the improvement

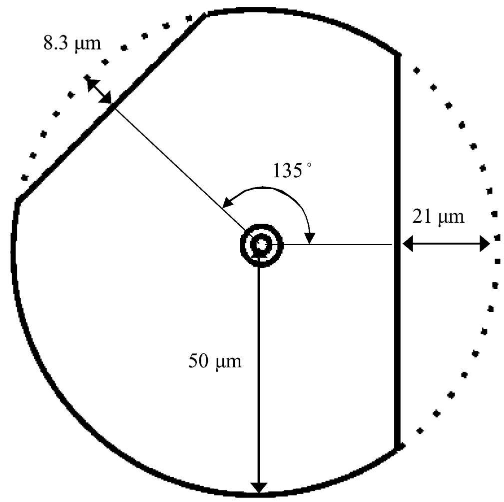

Fig. 5. Schematic of the fiber transversal cross-section geometry for the NDF used in experiments.

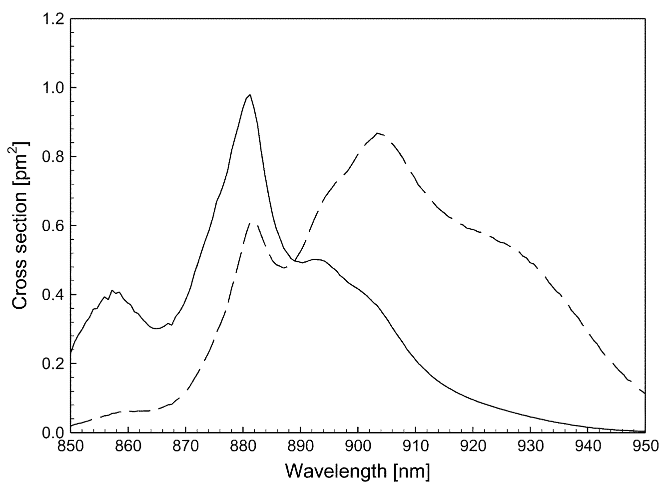

Fig. 6. Absorption (solid line) and emission (dashed line) cross-section spectra of aluminosilicate NDF used in the experiments.

in pump absorption, while the desired effect, the elimination of cladding modes with poor overlap with the core, accounts for only around two thirds of the improvement. The disadvantage is that the 19% reduction in the area of the inner cladding reduces the amount of pump power that can be launched. In this case, the reduction of the launched pump power was 11%, but this value will of course depend on the characteristics of the pump source.

Although the increase of the absorption may appear relatively modest, even small improvements can be important for a three-level laser. The increased pump absorption reflects a stronger interaction between the pump and the gain medium, which implies that the pumping will be stronger with the same pump power. As a consequence, it will be easier to reach threshold, even if the fiber length stays the same. Furthermore, the pump absorption per unit length varies along the fiber in double-clad fibers, since after some length of fiber, most of the remaining pump power will be in modes with low pump absorption. This effect is strong in circularly symmetric fibers, because of the large number of modes with small overlap with the core. Thus, while the untruncated fiber had an absorption of 7 dB over 14 m of fiber, a length of 30 m was required for

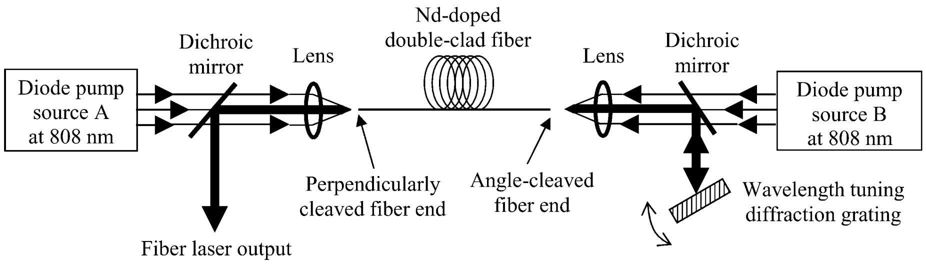

Fig. 7. Setup for 0.9-μm tunable NDFL.

12 dB of pump absorption. This leads to a decisive difference in performance. Note that though one can in principle increase the pump absorption in a circular fiber by scrambling pump modes using fiber bending, this was impossible in this case because of signal bending loss as shown in Fig. 4.

Finally, quenching and background losses must also be controlled for good conversion efficiency. The use of an aluminosilicate host makes this easier than with a germanosilicate host, as larger neodymium concentrations can be incorporated before concentration quenching via Nd^{3+} cross relaxation sets in. Nd^{3+} can also be quenched by OH^-, so the OH^--content should be low. We measured the Nd-concentration to 1.645×10^{19} ions/cm^3, and the fluorescence lifetime to 491 μs. This does not deviate from the unquenched lifetime of $\sim$500 μs.

Fig. 6 shows emission and absorption cross sections, as evaluated for our aluminosilicate NDF (neodymium-doped fiber). The emission cross-section spectrum peaks at 906 nm while the absorption spectrum peaks at 880 nm, within the $^4F_{3/2} - ^4I_{9/2}$ transition. The spectroscopy indicates that it is possible to tune the laser oscillation at least between 870–940 nm, provided that pump intensity reaches the threshold population inversion for 0.9-μm oscillation. The fraction of Nd^{3+} ions that has to be excited will be high for short wavelengths because of the high GSA, as well as for long wavelengths because of the low-emission cross section.

III. Laser Experiment and Results

The experimental laser configuration we used is shown in Fig. 7. The Nd-doped fiber was pumped by two 808 nm diode sources in a double-sided end-pumping scheme. The pump beams were focused onto the fiber ends by lenses with 8 mm focal length and 0.5 NA. The used NA was estimated to 0.4, as determined by the diameter of the pump beams incident on the lenses. Diode pump source A (PUMA, New-Optics, 808 nm) provided 4 W of launched pump power into a 100-μm-diameter inner cladding while pump source B (Unique Mode, 808 nm) provided 3.5 W of launched pump power. Dichroic mirrors separated the pump and signal beams at both ends of the fiber. The 4% Fresnel reflection from a perpendicularly cleaved fiber end and an external diffraction grating formed the laser cavity. To avoid laser instability caused by multiple reflection points, the grating end of the fiber was angle cleaved. The grating efficiency was measured at 915 nm and found to be 62% to the first order. We tuned the lasing wavelength by changing the angle of the diffraction grating. We used a relatively long fiber, 14 m or more, that provided adequate pump absorption (at least 12-dB operational pump absorption), to suppress pump crosstalk and prevent one pump source from damaging the other.

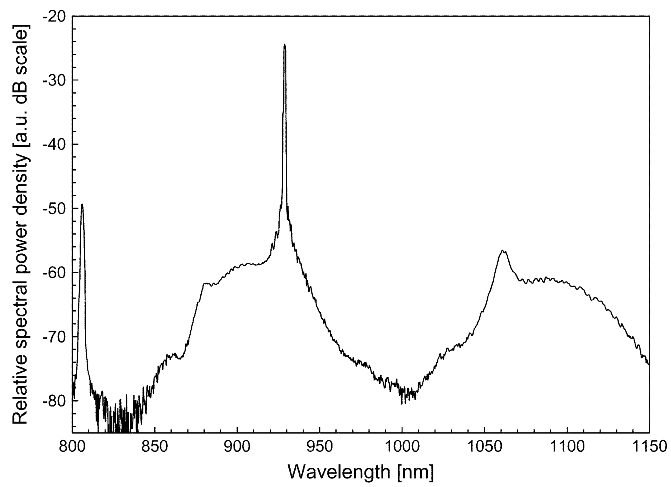

Fig. 8. Example of power spectrum of the 0.9-μm tunable fiber laser measured by OSA with resolution 1 nm (fiber length 14 m).

Fiber length is an important parameter of any fiber laser. For example, because of the wavelength dependence of the GSA, it will influence the tuning range [11]. We therefore report the laser characteristics at different fiber lengths. We started with a 25-m—long fiber and cut it back several times to finally stop at 14 m. For every fiber length, we determined the slope efficiency and the threshold pump power as well as the wavelength tuning range. At 14 m fiber, the operating, hot cavity, pump absorption was 12.1 dB. The maximum laser power occurred when the wavelength was tuned to 926 nm. The slope efficiency was 41% and threshold pump power was 1.62 W, both with respect to launched pump power. The maximum output power was 2.4 W. This was the highest power achieved. Fig. 8 shows a typical laser output spectrum, measured with an optical spectrum analyzer with a resolution bandwidth of 1 nm. The suppression of the competing 1.06-μm transition was excellent. The laser linewidth was 0.26 nm (FWHM) as measured with a resolution of 0.05 nm. The beam propagation parameter M^2 was 1.05 when the output power was 2 W, i.e., the output was diffraction limited.

Fig. 9 shows how the laser output power depends on pump power at different fiber lengths. For each length, the grating was tuned to provide maximum output power. This happened for wavelengths in the range 926–931 nm. As we cut back the fiber, the slope efficiency increased and the threshold pump power decreased, which is mainly due to signal propagation and reabsorption losses. It appears as if higher power would be possible

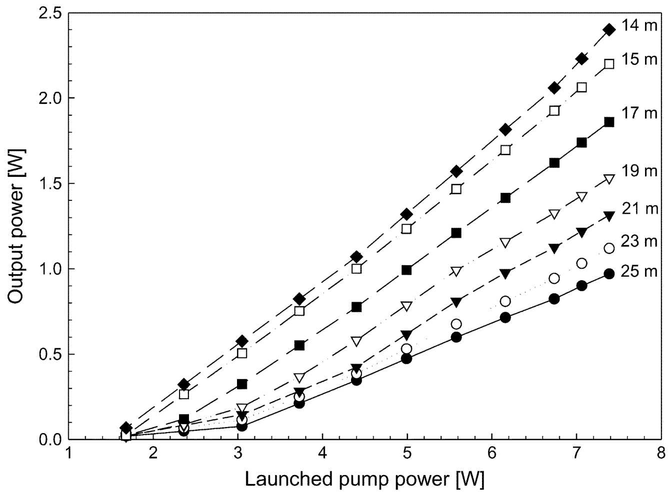

Fig. 9. Laser power characteristics at different fiber lengths.

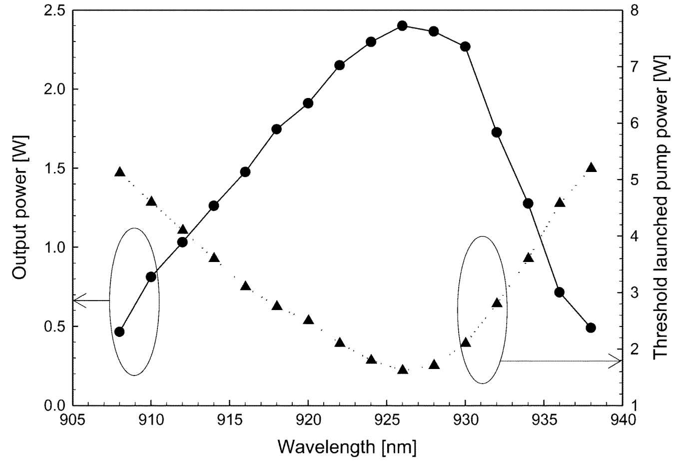

Fig. 11. Maximum output power and threshold pump power versus wavelength.

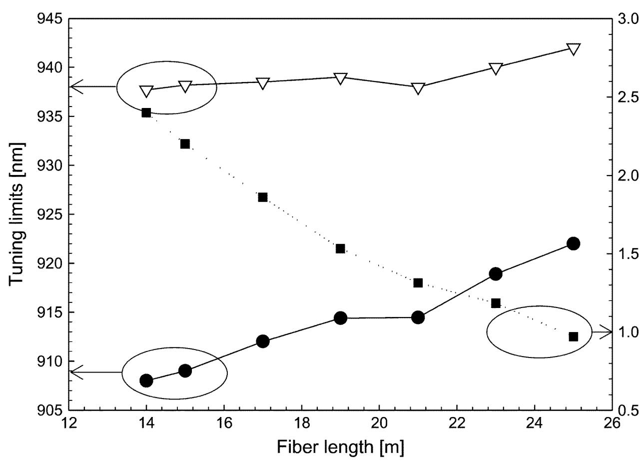

Fig. 10. Tuning range and maximum output power for different fiber lengths.

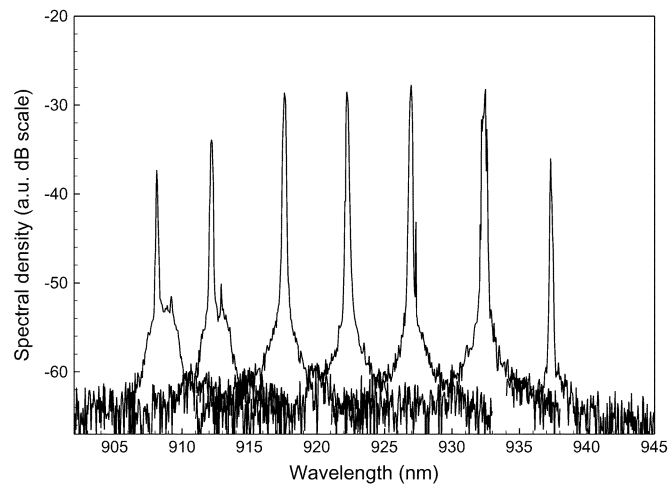

Fig. 12. Tunable laser spectrum of 14-m fiber (OSA resolution 0.05 nm).

if we further shortened the fiber, but this would jeopardize the pump sources so we refrained from doing this. However, with a smaller inner cladding, the pump absorption per unit length would increase. We could then use shorter fibers, with which the slope efficiency would probably be higher.

As expected, the tunability also changed with fiber length. This is shown in Fig. 10. The tuning range shifted to shorter wavelengths for shorter fibers, as is typical for long-wavelength (quasifour-level) operation of fiber lasers with GSA [11]. Thus, the tuning range was 908–938 nm for a 14-m-long fiber, and 922–942 nm for a 25-m-long fiber.

Fig. 11 shows the tuning curve at full pump power for a 14-m-long fiber. The maximum power occurred at 926 nm. The power at the edge of the tuning range dropped significantly because of the increasing threshold, also shown in Fig. 11. By contrast, variations in slope efficiency were small across the tuning range. This conclusively demonstrates that the waveguiding loss induced by W profile is negligible within the wavelength range of the laser, since any such loss would be negligible. A limiting factor for the tunability was, in practice, a strong gain at ~926 nm. This appeared when the diffraction grating was tuned to the edge of the tuning range, because of the large fraction of excited Nd-ions needed for lasing at the edge. As a consequence, 926 nm could start lasing from spurious reflections, e.g., from the angle-cleaved fiber end or the diffraction grating. We found that for better tunability the minimization of reflection from the angled-cleaved fiber end was critical. Such behavior is typical at high gains of 30 dB or more, which then suggests that our fiber would be capable of high-gain amplification at 926 nm. Finally, Fig. 12 shows laser output spectra for different tuning wavelengths between 908–938 nm, measured with 0.05-nm resolution. The measured linewidth was in each case 0.26 nm.

IV. Conclusion

We have described the characteristics of a cladding-pumped tunable neodymium-doped aluminosilicate fiber laser and their length dependence. The maximum output reached 2.4 W with 41% slope efficiency and 1.68-W pump threshold, both with respect to launched pump power. The fiber core had a W-type refractive index profile that effectively suppressed the competing emission at 1.06 μm. The laser was tunable from 908 to 932 nm with a shorter fiber and from 922 to 942 nm with a longer fiber.

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