High-power single-frequency 1014.8 nm Yb-doped fiber amplifier working at room temperature

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A single-frequency 1014.8 nm Yb-doped fiber amplifier working at room temperature was investigated in detail with respect to gain fiber length, fiber geometry, and fiber host material, which can be frequency quadrupled to 253.7 nm for laser cooling of mercury. After optimization, an up to 8.06 W laser was achieved with a single-stage amplifier, and 19.3 W power was obtained with another boost amplifier, using polarization-maintaining Yb-doped single-mode fiber with a 10 μm core and 125 μm inner clad. The amplified spontaneous emission was 25 dB lower than the signal in the final output of the laser system. The laser has a linewidth of ~24 kHz without noticeable broadening after amplification. Further power scaling is limited by stimulated Brillouin scattering.

OCIS codes: (140.3280) Laser amplifiers; (140.3510) Lasers, fiber; (140.3320) Laser cooling; (140.3615) Lasers, ytterbium.

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1. Introduction

In the past decade, Yb-doped fiber lasers and amplifiers have received a lot of attention and experienced very fast development, due to the availability of high-power diode pump lasers, the small quantum defect of the laser transition, and the double-cladding pumping technique [1]. Yb-doped fiber lasers and amplifiers can operate at the wavelength range from 950 to 1200 nm in principal. While the center of gain is around 1060 nm, we are interested in lasers at wavelengths from 1010 to 1025 nm, which are needed for several applications. They can be used in laser cooling of Yb-doped solids [2,3]. A frequency-doubled laser at 507 nm can serve as a clock laser in optical lattice clocks based on the $^1S_0$–$^3P_2$ transition of ytterbium atoms [4]. Furthermore, mercury, being the heaviest nonradioactive atom that has been laser-cooled and trapped, is probably the best candidate for an optical lattice clock due to the potential uncertainty of the 10^{-18} level [5]. Its laser cooling and trapping requires a narrow-frequency tunable laser at 253.7 nm (frequency quadrupling of 1014.8 nm), which corresponds to the $^1S_0$–$^3P_1$ transition of mercury [5,6]. Besides, 253.7 nm is also one of the fundamental wavelengths for four-wave sum frequency mixing in mercury vapor, to generate cw vacuum-UV radiation around 121 nm for future laser cooling of trapped antihydrogen [7].

Several 1014.8 nm lasers based on solid-state or semiconductor laser media have been reported to generate a 253.7 nm laser by frequency quadrupling [6,8,9], and the highest reported power to date was a

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7 W, 1014.8 nm Yb:YAG disk laser by Petersen *et al.* [5]. In 2006, Seifert *et al.* reported a 5 W two-stage amplifier at 1014.8 nm based on Yb-doped double-clad fiber, with a linewidth of less than 3 MHz [10]. Recently, Steinborn *et al.* reported their 10 W fiber amplifier based on a large-mode double-clad fiber [11]. However, the Yb-doped fibers were cooled to liquid nitrogen temperature, in order to reduce the absorption at the signal wavelength. The significant absorption of Yb-doped fiber at 1014.8 nm under room temperature facilitates the amplified spontaneous emission (ASE) at longer wavelengths (about 1030–1040 nm), where the emission cross sections are usually larger. A high-power 1014.8 nm fiber amplifier working at room temperature would be highly favored for its reduced complexity.

Recently, we reported all-fiber-connectorized 1014.8 nm single-frequency amplifiers at room temperature [12], proving that it's not essential to cool the Yb-doped fiber to liquid nitrogen temperature. 8 W cw linearly-polarized single-transverse-mode laser output was achieved. With two resonant cavity frequency doublers, 75 mW laser at 253.7 nm was generated from 4 W, 1014.8 nm laser [12]. Since both the absorption spectrum and saturated absorption spectrum of the $^1S_0$–$^3P_1$ transition of atomic mercury have been measured with this UV radiation [12], this room-temperature 1014.8 nm Yb-doped fiber amplifier is applicable for mercury cooling. In this paper, we present the study of amplifier performance and optimization in detail. Three types of Yb-doped double-clad fibers of different geometries and host materials have been investigated with regard to amplifier performance, as well as fiber length and seed power. By adding an extra fiber amplifier, maximum 19.3 W laser is achieved, which is limited by stimulated Brillouin scattering (SBS). To the best of our knowledge, this is the highest power reported for a single-frequency fiber laser at this wavelength region.

2. Experimental Setup

The experimental setup is a diode master oscillator fiber power amplifier system, as shown in Fig. 1. The seed laser comes from an external cavity diode laser with a tapered amplifier at 1014.8 nm (Toptica TA Pro), which is linearly polarized and has an output spot of oval shape. After being reshaped by two cylindrical lenses, the light is coupled into a polarization-maintaining (PM) single-mode fiber (PM980). $(2+1)\times 1$ pump and signal combiners are used to introduce the pump diode lasers at 975 nm into the inner clad of gain fiber. The unabsorbed pump power is damped with pump strippers, and the fiber output is angle cleaved to avoid back reflections. The experiments start with tests of the 1014.8 nm amplification at room temperature by a single-stage amplifier. Three types of commercial double-clad Yb-doped fiber that would allow single-mode operation for a laser at 1 μm are tested, and their parameters are shown in Table 1. The influences of gain fiber length and seed power on laser performance are studied as well. Then a second stage amplifier is added for power scaling. To reduce the ASE in the seed laser for the second stage amplifier, i.e., the output of the first stage amplifier, a fiber pigtailed ASE filter is inserted between the two stages, whose transmission spectrum is shown in the inset of Fig. 1. The filter is based on a Semrock bandpass filter (FF01-935/170-25). The whole amplifier system is fiber-connectorized and all-PM.

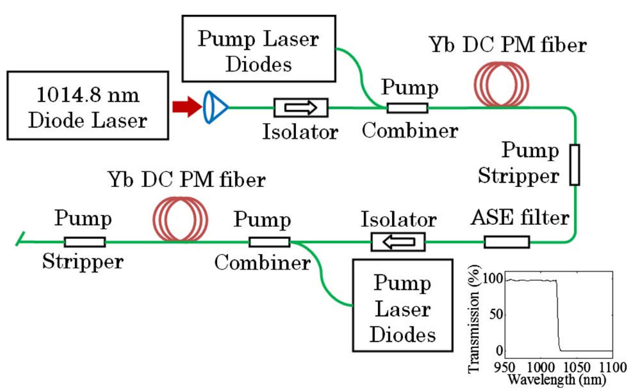


Fig. 1. Schematic diagram of the experimental setup.

Table 1. Parameters of the Yb-doped Fibers under Test

Fiber	Core Diameter (μm)	Core Numerical Aperture	Inner Clad Diameter (μm)
5/130	5	0.12	130.0 ± 1.0
10/125	11 ± 1.0	0.075	125 ± 2.0
8/128	8	0.10	128

Fiber	Nominal absorption rate near 975 nm (dB/m)	Host materials	Polarization maintaining
5/130	1.8	Aluminosilicate	Yes
10/125	4.8	Aluminosilicate	Yes
8/128	10.8	Phosphosilicate	No

3. Experimental Results and Analysis

We investigate 5/130 gain fiber first. Indeed, at room temperature, ASE at ~1035 nm is a severe problem. Figure 2 shows the output spectra of a fiber amplifier

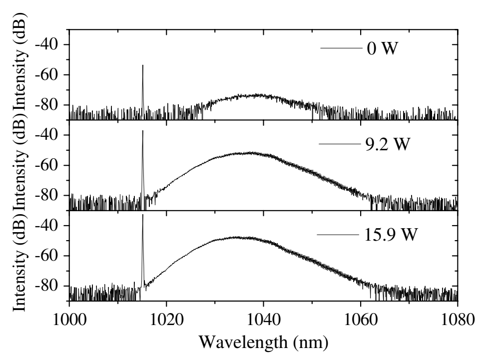


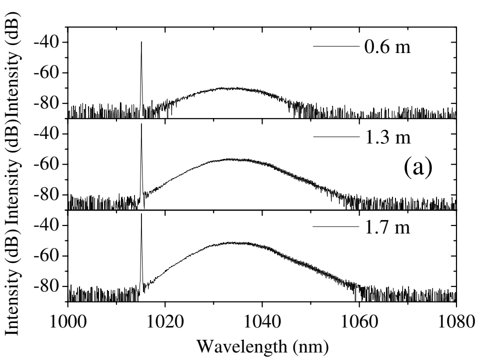
Fig. 2. Direct output spectra at different pump powers: 0, 9.2, and 15.9 W, respectively. The gain fiber is 2 m long 5/130 fiber, and the seed laser is about 130 mW.

with 2 m long 5/130 gain fiber, at pump powers of 0, 9.2, and 15.9 W. When there is ~130 mW seed laser only (without pump laser), the ASE is already detected. As the pump power increases, the ASE grows rapidly and peaks at ~1035 nm. It increases much more quickly than the signal, as seen from the decreasing difference between the laser and the ASE peak level.

A. Dependence on Fiber Length

To reduce the fraction of ASE in the output, amplifiers with different fiber lengths are tested. Figure 3(a) shows the direct output spectra without ASE filtering for 5/130 fiber lengths of 0.6, 1.3, and 1.7 m at a pump power of 19.2 W and a seed power of 130 mW. The proportion of ASE in the total output decreases as the gain fiber becomes shorter, which is more obvious from the increasing difference between the total output power and forward ASE power in Fig. 3(b). Figure 3(b) also shows the laser power as a function of the fiber length. Since the pump absorption is less with shorter fiber, the total output is lower. But the signal power increases instead and peaks around 1.2 m, as a result of decreasing ASE. When the gain fiber is too long (2.3 m), the forward ASE decreases as well, which is due to the faster increase of backward ASE.

Therefore, shortening the gain fiber is effective in decreasing ASE but sacrifices pump absorption and laser efficiency. The maximum laser power with 5/130 fiber is just 1.88 W, with an optical efficiency of 9.7%, because of the severe ASE. 41.9% of the total output is forward ASE. Even higher ASE power is expected in the backward direction. A good understanding of the competition between the laser amplification and ASE in the 1014.8 nm Yb-doped fiber amplifier is necessary to improve the amplifier performance when operating at room temperature.



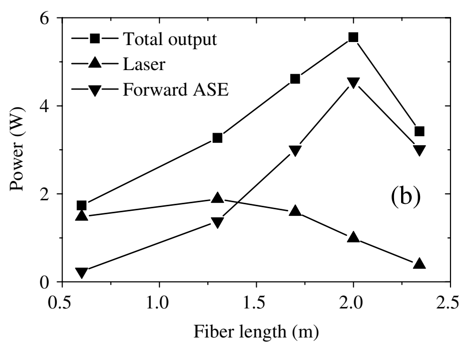


Fig. 3. (a) Spectra of the amplifier's direct output with 5/130 fiber lengths of 0.6, 1.3, and 1.7 m, respectively, (b) the total output, the laser output, and the forward ASE power as functions of the gain fiber length. The pump power is 19.2 W, and the seed power is ~130 mW.

B. Theoretical Analysis

Usually Yb-doped silica fibers are considered as a homogeneously broadened gain medium at room temperature. In such a medium, the gain G (in dB) is given by [13,14]

$$G(\lambda) = kN_0A_d\Psi_d(\lambda)\{[\sigma_e(\lambda) + \sigma_a(\lambda)]n_2 - \sigma_a(\lambda)\}L, \quad (1)$$

where $k = 4.343$, N_0 is the concentration of Yb ions, Ψ_d is the normalized modal intensity averaged over the doped area A_d, σ_e and σ_a are the cross sections for stimulated emission and absorption, respectively, n_2 is the fraction of excited active ions, and L is the active fiber length. Equation (1) implies that the gain G^A at one wavelength is determined by the gain G^B and G^C at two other wavelengths:

$$G^A = G^B(\Psi_d^A/\Psi_d^B)\frac{(\sigma_e^A/\sigma_e^C - \sigma_a^A/\sigma_a^C)}{(\sigma_e^B/\sigma_e^C - \sigma_a^B/\sigma_a^C)} + G^C(\Psi_d^A/\Psi_d^C)\frac{(\sigma_e^A/\sigma_e^B - \sigma_a^A/\sigma_a^B)}{(\sigma_e^C/\sigma_e^B - \sigma_a^C/\sigma_a^B)}, \quad (2)$$

where the superscripts distinguish quantities at the three wavelengths λ^A, λ^B, and λ^C, respectively [14].

In this study, the fiber amplifier is limited by the ASE, which is believed to become strong at ~40 dB gain and will grow rapidly for higher gain. Therefore, we'd like to consider the relation between the gain of signal, the gain of the ASE peak, and the pump absorption (negative gain). For the signal laser and ASE light guided in the core, the modal intensity Ψ_d varies slowly with wavelength and is considered the same; for pump light guided in the inner clad, Ψ_d^s/Ψ_d^p is approximately equal to the area ratio $A_{\mathrm{clad}}/A_{\mathrm{core}}$ [14].

Therefore, with the emission and absorption spectra of Yb-doped aluminosilicate fiber provided by the manufacturer, the gain at 1015 nm, G_{1015}, is related to the gain at the ASE peak and absorption (negative gain) at 976 nm, α_P, by

$$G_{1015}^{Al} = \frac{G_{1035}^{Al}}{1.13} - 0.0375\frac{A_{\mathrm{clad}}^{Al}}{A_{\mathrm{core}}^{Al}}\alpha_p^{Al}. \quad (3)$$

The formula is in agreement with the experiment on fiber length dependence. As the gain fiber becomes shorter, pump absorption decreases. Then the difference between the gain of 1015 nm and the ASE decreases, which leads to a higher proportion of signal in the total output.

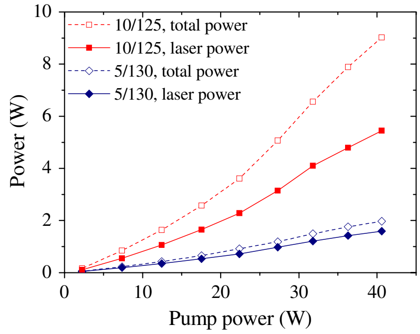


Fig. 4. Total power and laser power of the 5/130 and 10/125 fibers, respectively. The amplifier is composed of ~85 cm gain fiber and is seeded with 30 mW.

C. Dependence on Fiber Geometry

According to Eq. (3), to achieve the same gain with the ASE under control, a fiber with a smaller clad-to-core ratio allows better pump absorption. Higher pump absorption will lead to higher amplifier efficiency. Figure 4 shows the total output and laser power without ASE as functions of the pump power, for gain fiber of 85 cm 5/130 fiber and 10/125 fiber, and the seed power is 30 mW. The powers increase nonlinearly due to the redshift of the pump diode wavelength with power, which approaches the Yb absorption peak of 976 nm at the highest power. As expected, the amplifier with 10/125 fiber is more efficient and generates more power compared to the 5/130 fiber. Also, a higher proportion of ASE is seen in the 10/125 fiber amplifier output, because of the lower seed laser intensity and higher pump absorption than in the 5/130 fiber.

D. Dependence on Fiber Host Material

Since the exact energy gaps between the Stark levels of the Yb ions depend on the host glass chemical composition [15], the absorption and emission cross sections will differ. The room temperature emission and absorption spectra of Yb-doped aluminosilicate and phosphosilicate fibers provided by the manufacturers are shown in Fig. 5. Both the absorption and emission cross sections of the aluminosilicate fiber are larger, especially in the range of 850–970 nm for absorption and 1000–1100 nm for emission. The phosphosilicate fiber is less sensitive to changes in the pump wavelength between 910 and 976 nm, since the absorption cross section varies less in this range. More importantly, the absorption at 1015 nm is less and the emission peak is blue-shifted. In fact, the ASE in the amplifier with phosphosilicate fiber peaks at ~1025 nm.

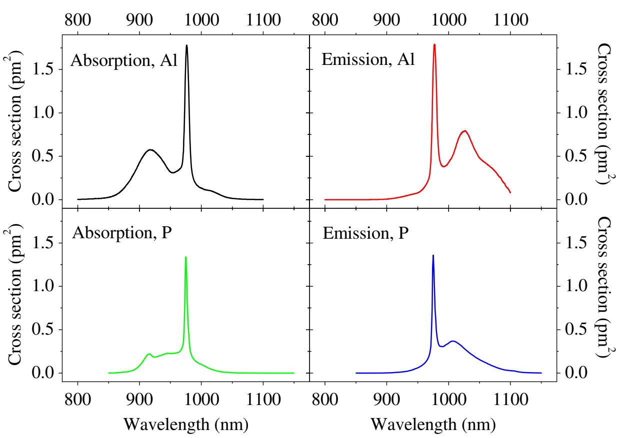


Fig. 5. Absorption and emission cross-section spectra of the Yb-doped fiber we used.

According to Eq. (2) and Fig. 5, the equation of Yb-doped phosphosilicate fibers, similar to Eq. (3), is

$$G_{1015}^{P} = \frac{G_{1025}^{P}}{0.88} - 0.0168\frac{A_{\mathrm{clad}}^{P}}{A_{\mathrm{core}}^{P}}\alpha_{p}^{P}. \quad (4)$$

From Eqs. (3) and (4), it's evident that the phosphosilicate fiber is superior compared with aluminosilicate fiber for amplification of a 1014.8 nm laser. Under the same 40 dB gain limit of ASE, there will be higher upper boundaries of G_{1015} and smaller differences between the gains of signal and ASE. Figure 6 shows the total output power and amplified laser power with the 10/125 aluminosilicate fiber and the 8/128 phosphosilicate fiber. The 8/128 phosphosilicate fiber is chosen for comparison because of similar fiber geometry. Both fibers are ~1 m long, and the seed laser power is 30 mW. The power curves for the 8/128 phosphosilicate fiber is more linear compared with the curves of 10/125 aluminosilicate fiber, indicating that it's less sensitive to the pump wavelength shift. Though the 8/128 fiber's pump absorption rate is much larger, the total output is slightly lower, which may be due to the extra loss caused by the mismatching between the non-PM 8/128 fiber and the PM passive signal fiber of the pump and signal combiner. Nevertheless, both the laser power and its proportion in the total output are slightly higher, in agreement with the theory, though the 8/128 fiber has a larger clad-to-core ratio. Unfortunately, parasitic oscillation occurs when the pump power exceeds 25 W in our experiments, and the reason is still not clear.

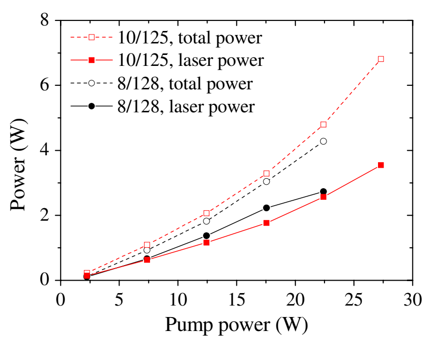


Fig. 6. Total output power and laser power of the 8/128 and 10/125 fibers. The fiber is ~1 m long, and the seed power is 30 mW.

E. Performance of the Optimized Single-Stage Amplifier

Based on above results, the 10/125 fiber is selected, and there should be an optimum fiber length, which is about 1 m as reported in [12]. The influence of the seed power on the amplifier performance was investigated, and the laser output power saturates as the seed power is higher than the saturation power at 1014.8 nm (~31 mW for 10/125 fiber) [12].

The performance of the single-stage amplifier was reported in [12]. A maximum 8.06 W laser output with an optical efficiency of 18% is obtained with 100 mW seed power and 1.05 m 10/125 fiber. The amplifier output is linearly polarized (~15 dB polarization extinction ratio), and its linewidth is ~24 kHz, measured by the self-heterodyne method and Lorentzian fitting. No linewidth broadening during amplification is observed.

With two commercial external cavity frequency doublers, 1.03 W green laser at 507.4 nm and 75 mW UV laser at 253.7 nm are generated from a maximum allowed input fundamental power of 4 W (specified by the manufacturer) [12]. With this UV radiation, both absorption and saturated absorption spectra of the $^1S_0$–$^3P_1$ transition of atomic mercury were measured, proving that this Yb-doped fiber amplifier is suitable for mercury cooling [12].

F. Performance of the Boost Amplifier

To further raise the laser power, a boost amplifier is added after the first amplifier described above. The gain fiber is still 10/125 fiber, and its length is chosen to be 1.4 m, a little longer considering the higher seed power. A fiber pigtailed ASE filter is inserted between the two amplifiers in order to limit the ASE, whose transmission spectrum is shown in Fig. 1.

Figure 7 shows the output laser power and forward ASE power of the boost amplifier as functions of the pump power, when the seed laser is 3.1 and 3.6 W, respectively. The forward ASE increases nonlinearly as usual, but the laser output curves have a roll-over at end, which is due to the emergence of SBS. The boost amplifier is investigated with varying seeding power. As Fig. 8 shows, at low pump power, the laser power increases almost linearly with respect to the seed power. As pump power increases to a certain level, the laser output power starts roll-over with respect to the seed power. With higher seed power, the laser output drops instead, which is a signature of SBS.

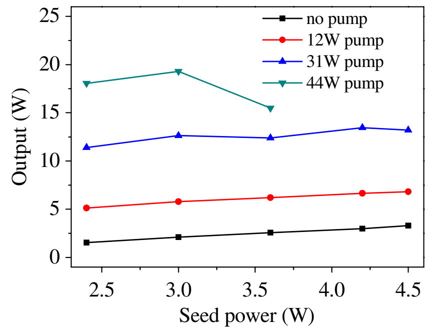


Fig. 8. Laser power as a function of the seed power for the boost amplifier, under different pump powers.

The maximum achieved output is 19.3 W, with an efficiency of 33.5% and a seed power of ~3.1 W. To the best of our knowledge, this is the highest power reported for a single-frequency Yb-doped fiber amplifier at this wavelength region. The efficiency is higher than the first stage amplifier due to the larger seeding power and longer gain fiber length, which allows better pump absorption. Though at the highest output the forward ASE reaches 9.3 W, the ratio of forward ASE to laser (0.48) decreases compared with that of the first stage amplifier (0.82). The ASE in the output peaks at ~1020 nm instead of 1035 nm, because of the residual ASE peak at ~1020 nm in the filtered first stage amplifier, as Fig. 9 shows. Also, the ASE at longer wavelengths seems to be suppressed because of the larger seeding power. The peak is 24.7 dB lower than the signal and 25.6 dB lower after inserting a bandpass filter. Because the following two frequency doubling cavities are effective narrowband filters, only the local ASE level at the laser wavelength of 1014.8 nm could affect the overall performance of the laser, which is ~43 dB below the signal. The previous frequency-quadrupling experiments have confirmed that the residual ASE would not be problematic.

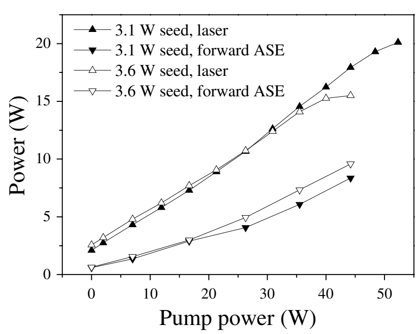


Fig. 7. Laser power and the forward ASE power of the boost amplifier as functions of pump power, when the seed is 3.1 and 3.6 W, respectively.

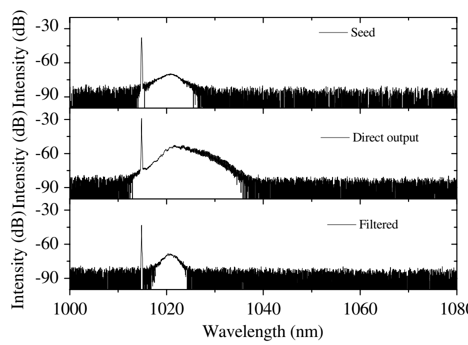


Fig. 9. Seed, direct output, and filtered output spectra of the boost amplifier. The seed power is 3.1 W, and the pump power is 48.4 W.

4. Conclusion

We have investigated 1014.8 nm Yb-doped fiber amplifiers working at room temperature with respect to gain fiber length, fiber geometry, and fiber host material. Yb-doped fiber has a significant absorption at 1014.8 nm at room temperature, and amplification at this wavelength is limited by the ASE at longer wavelengths. We report that by properly designing the fiber amplifier, cooling of the Yb-doped fiber is not required, which was considered necessary in the past. Our study has verified that it's favorable to use gain fibers with a smaller clad-to-core ratio for amplification of the laser at a wavelength around 1014.8 nm. Furthermore, Yb-doped phosphosilicate fibers would be a promising candidate, if parasitic oscillation is restrained.

8.06 W single-frequency single-mode linearly polarized laser output was achieved by a single-stage amplifier, and 19.3 W was achieved by two-stage amplification at room temperature, limited by SBS. The linewidth was measured to be $\sim$24 kHz by the self-heterodyne method without noticeable broadening. Preliminary experiments on frequency quadrupling to 253.7 nm and absorption spectroscopy of the $^1S_0$–$^3P_1$ transition of atomic mercury demonstrate that the fiber-amplifier-based laser is suitable for laser cooling of mercury atoms.

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