



A Narrow-Linewidth Linearly Polarized 1018-nm Fiber Source for Pumping Diamond Raman Laser

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A 7.8-GHz linewidth ytterbium-doped fiber (YDF) laser with an output power of 75 W at 1,018 nm is demonstrated based on narrow-bandwidth fiber Bragg gratings. Effective suppression of spectral broadening and amplified spontaneous emission is achieved by optimizing the resonator structure and active fiber parameters. An 1,178-nm diamond Raman output pumped by this narrow-linewidth 1,018 nm source is addressed in this study, which shows a promising application of generating the sodium guide star laser at 589 nm. A single-longitudinal-mode Stokes with an output power of 0.6 W is obtained using this multimode 1,018 nm laser at the pump power of 13 W. The impact of pump spectral linewidth on the effective Raman gain coefficient is analyzed, and the laser threshold of the diamond Stokes resonator increases with the broadening of the pump linewidth.

Keywords: fiber laser, stimulated Raman scattering, second harmonic generation, solid state laser, diamond Raman laser

INTRODUCTION

High-power 1,018 nm ytterbium-doped fiber (YDF) lasers [1–7] are attractive pump sources. In tandem-pumping configurations, 1,018 nm fiber lasers have been widely harnessed to pump YDF amplifiers and random fiber lasers, due to their advantages of low quantum defect, high beam brightness, and high efficiency. Besides, narrow spectral-linewidth 1,018 nm lasers are of intense interest for many applications in beam combining laser subsystem [8], frequency converted to 509 and 254 nm for laser spectroscopy [9] and atom trapping [10].

A promising application using high-power narrow-linewidth 1,018 nm fiber lasers is as the pump for a diamond Raman laser to generate 1,178 nm output through the first-order diamond Raman shift (39.99 THz). Frequency-doubled 1,178 nm lasers [11, 12] provide a crucial application for the adaptive optics system, acting as sodium laser beacon. The Raman gain profile of the diamond pumped by a single frequency source is a Lorentzian shape with a full-width at half-maximum (FWHM) linewidth of 45 GHz [13]. Pumped with a narrow-linewidth laser, a single-longitudinal-mode (SLM) Stokes output was directly available in a diamond Raman resonator due to the homogeneous Raman gain profile and the absence of spatial hole burning effect [14]. The combination of diamond's ability to rapidly dissipate heat [15] and its gain nature of spatial hole burning free provides a pathway toward high-power SLM lasers. Our recently reported work, where SLM powers of 11.8 W at 1,240 nm and 38 W at 620 nm were achieved in a simple standing-wave diamond Raman frequency-doubling cavity pumped by a 1,064-nm laser with 3.3 GHz

linewidth [16], brings forth a promising approach to demonstrate a high-power SLM 589 nm laser by exploiting a narrow-linewidth 1,018 nm pump.

For optical fiber lasers, spectral linewidth broadening, induced by fiber nonlinearity and dispersion [17–20], is the main challenge of generating narrow-linewidth lasers with a high output power. The output spectral linewidth of 1,018 nm emitting with an output power of around 100 W has been still more than 75 GHz [21, 22]. Another main challenge is the amplified spontaneous emission (ASE) at around 1,030 nm due to its higher gain in YDF than that at 1,018 nm. This is understood as follows. In a homogeneously broadened gain medium such as Yb-doped silica fiber, the gain at one wavelength is uniquely determined by the gain at two other wavelengths [23, 24]. Assuming pumping at 976 nm, the ASE gain at 1,030 nm is calculated by, $G^{1030} = 1.41G^{1018} - 0.0324 \frac{1}{\beta} G^{976}$ where β is approximately equal to the ratio of fiber core to cladding. Therefore, the ASE gain at 1,030 nm decreases rapidly with increasing the fiber core-to-cladding ratio.

In this article, a linewidth of 7.8 GHz linearly polarized 1,018 nm YDF laser is demonstrated. At a pump power of 118 W, output power of 75 W was achieved corresponding to an optical to optical conversion efficiency of 64%. To the best of our knowledge, this is the narrowest linewidth reported of 1,018 nm fiber laser at this output power level. The 1,018 nm

fiber laser was successfully used to generate the first-order Stokes laser at 1,178 nm in a standing-wave diamond Raman resonator. The 1,178 nm output characteristics were also experimentally investigated.

EXPERIMENTAL SETUP

The schematic of experimental setup is shown in **Figure 1**. The 1,018 nm YDF laser is formed with a fiber resonator and a one-stage of YDF amplifier. A 27-W 976-nm laser diode (LD) was coupled into the fiber resonator as the pump through a combiner. The linear fiber resonator consisted of a pair of fiber Bragg gratings (FBGs) and 1.5 m long active fiber. The reflectivities of the high reflecting (HR) and output coupling (OC) FBGs were 98.5 and 17%, respectively. The center wavelengths of two FBGs were both located at about 1,017.9 nm with bandwidths of 0.4 and 0.08 nm, respectively, shown in the inset of **Figure 1**. The active fiber was a large core-to-cladding ratio Yb-doped double-cladding fiber with core and cladding diameters of 15 and 130 μm (LMA-YDF-15/130), and an absorption of 5.40 dB/m at 976 nm. A length of 50 m passive fiber (LMA-GDF-15/130) was fused between the active fiber and OC-FBG in order to increase the optical length of the oscillator. A fast-axis blocked polarization-maintaining (PM) optical isolator was inserted

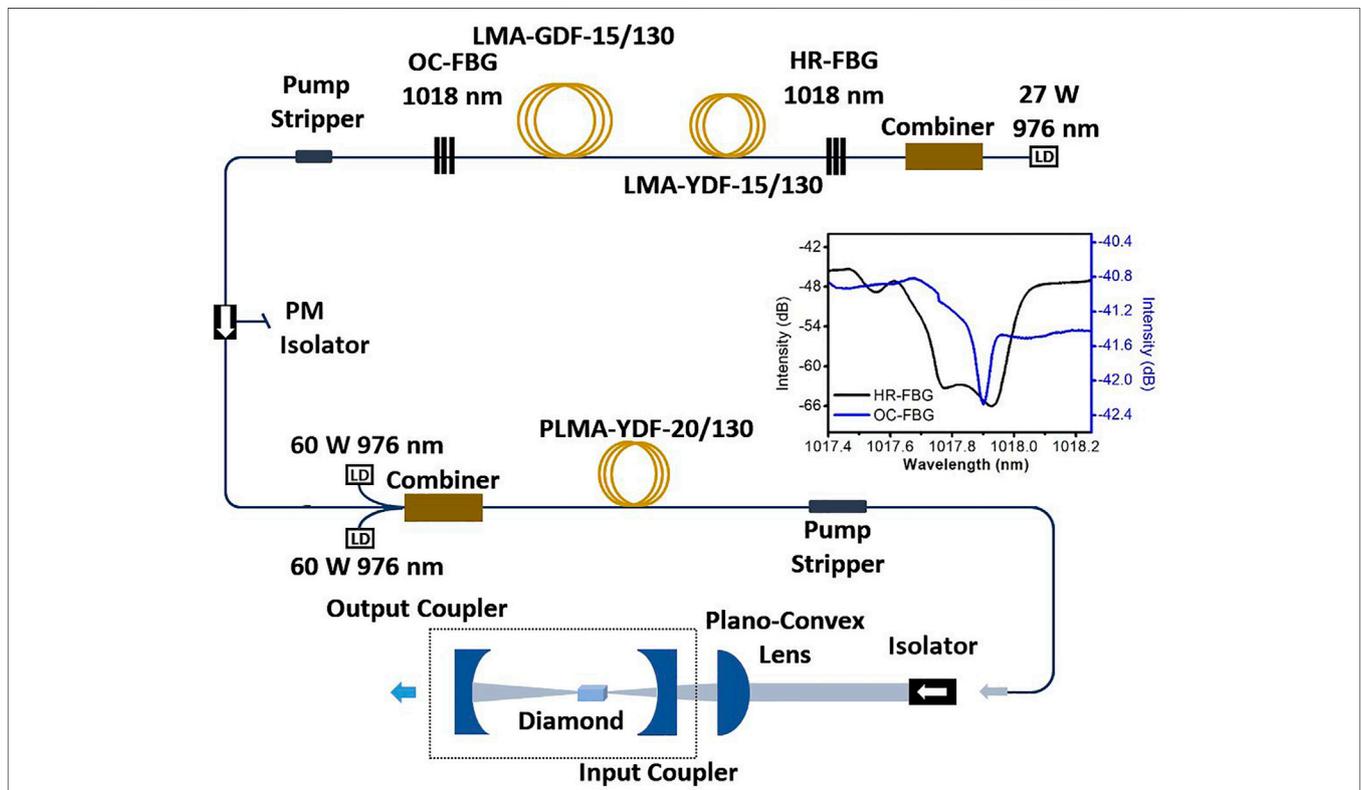
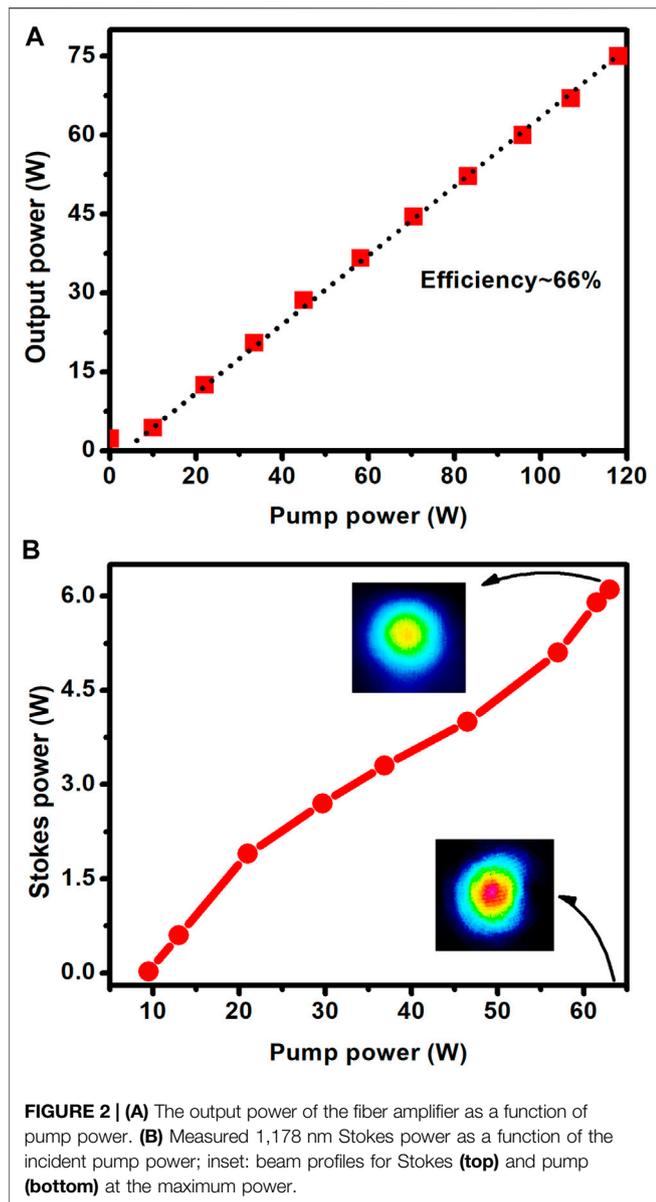


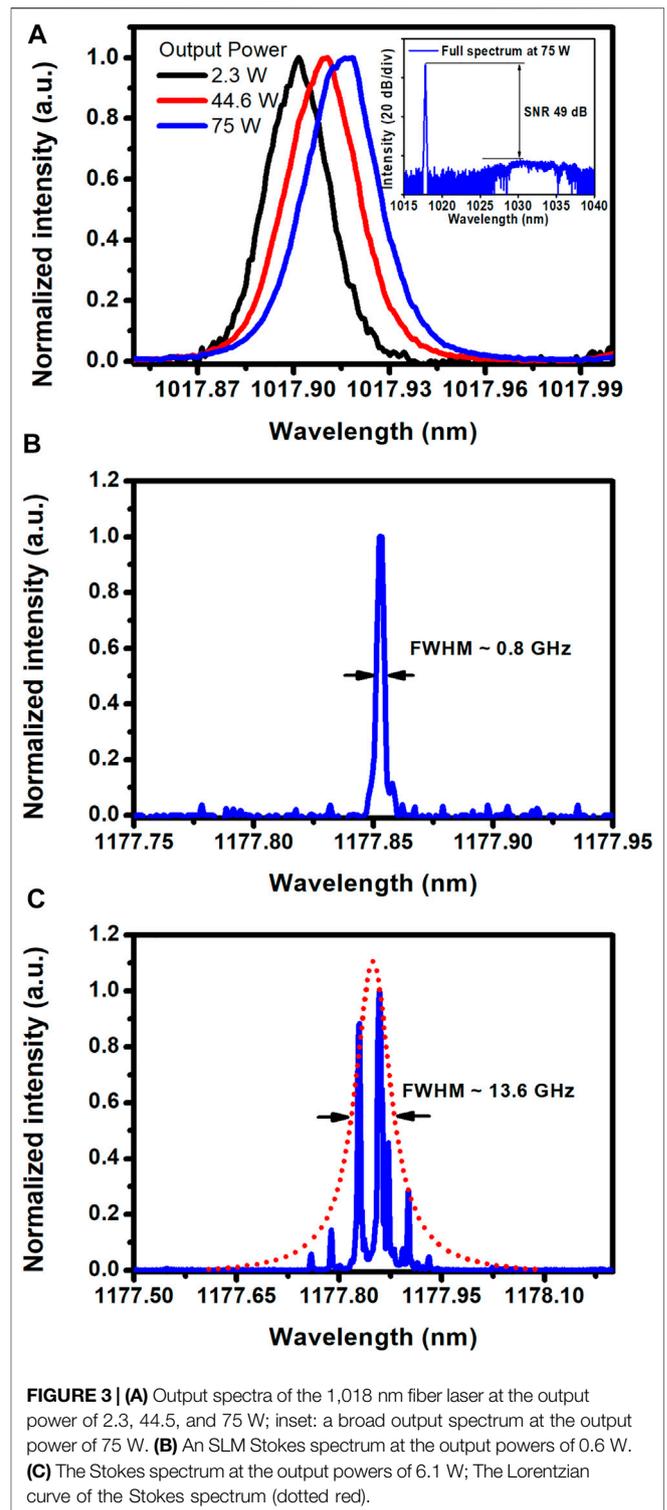
FIGURE 1 | Diagram of 1,018 nm fiber laser and 1,178 nm diamond Raman laser (dotted box). LD: laser diode; PM: polarization maintaining; PLMA: polarized large mode area; YDF: Yb³⁺-doped fiber; GDF: germanium-doped fiber; HR FBG: highly reflective fiber Bragg grating; OC FBG: output-coupling fiber Bragg grating; 15/130 and 20/130: fiber core diameter of 15 or 20 μm , and a fiber-cladding diameter of 130 μm . The inset is the transmission spectra of HR (black) and OC (blue) FBGs.



between the resonator and amplifier to enable only slow-axis polarized light passing and prevent the backward feedback into the resonator. In the fiber amplifier, two 60 W 976 nm LDs and a length of 0.9 m with core/cladding diameters of 20/130 μm PM LMA Yb-doped double cladding fiber (10 dB/m at 976 nm) were used to provide the pump and gain, respectively. Two pump strippers were used to remove the residual pump of the resonator and amplifier.

RESULTS AND DISCUSSION

- The 1,018 nm resonator was an all non-PM fiber connected linear structure. The length of active fiber was optimized to 1.5 m. The fast-axis blocked isolator acting as a polarizer enabled a linearly polarized output. The output power of the



1,018 nm seed laser was measured after the PM isolator. The threshold was about 1.5 W, and the output power increased to 2.6 W at the pump power of 11.8 W. **Figure 2A** depicts the output power of the amplifier as a function of pump power. When the pump power increased up to 118 W, the

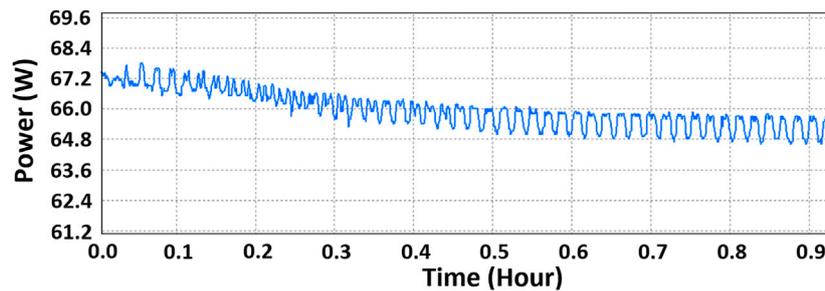


FIGURE 4 | Output power stability evolution of the 1,018 nm fiber laser after the free-space isolator.

output power of 75 W was achieved corresponding to an optical-to-optical conversion efficiency of 64%. The maximum output power was limited by the available pump power. The output polarization extinction ratio was only about 12 dB at the output power of 75 W due to the insufficient polarization extinction ratio of the PM isolator.

- The output spectra of the 1,018 nm laser were analyzed using a spectrometer (HF-8997-2, LightMachinery; resolution of 0.8 GHz) equipped with an InGaAs camera. As is shown in **Figure 3A**, the spectrum of the seed laser was centered at 1,017.90 nm and had a FWHM linewidth of 6.6 GHz. The longitudinal mode spacing of the seed laser spectrum was about 1.9 MHz, corresponding to an oscillator length of about 53 m. The narrow spectral linewidth was generated by exciting partial longitudinal modes within the FBG reflection bandwidth due to a low-power pumping. In order to suppress spectral broadening and ASE, the length of the large core-cladding ratio gain fiber (PLMA 20/130) in the amplifier was shortened to 0.9 m. The spectral FWHM linewidth was slightly broadened from 6.6 to 7.8 GHz as the output power was increased from 2.3 to 75 W, as shown in **Figure 3A**. The slight redshift of central wavelength was observed due to the thermal induced refractive index decrease of the silica fiber. A broad spectrum at output power of 75 W was measured using an optical spectrum analyzer (YOKOGAWA, AQ6370B) with a resolution of 0.02 nm. The inset in **Figure 3A** depicts that the signal-to-noise ratio (SNR) between 1,018 and 1,030 nm was 49 dB, indicating excellent suppression of the ASE.
- A FBG resonator-based fiber laser usually has a temporal profile with high intensity fluctuation due to longitudinal modes beating. The intensity fluctuations of the pump laser is transferred to the stimulated Raman scattering process due to the short response time [25]. The resonator consists of a spool of 50 m passive fiber to decrease the longitudinal mode spacing and thus increase the number of longitudinal modes. Due to the longitudinal modes with random phases, the intensity fluctuations caused by modes beating decreased with the increase of the number of modes. The amplified 1,018 nm laser was collimated by a commercial pigtailed collimator which delivered an output beam diameter of 1.3 mm.

- The collimated continuous-wave (CW) 1,018 nm laser was injected into a standing-wave diamond Raman cavity after passing through a free-space isolator and a plano-convex focusing lens ($f = 50$ mm), shown in the dotted box in **Figure 1**. The output power evolution of the pump laser, measured after the free-space isolator, in about 1 h is shown in **Figure 4**. The starting power was 67.4 W, corresponding to a total loss of 10% that resulted from the collimator and isolator. The output power decreased slowly from 67.4 to 65.4 W in the first half hour, during which the laser diode and the gain fiber of the amplifier reached thermal stability. In the next half hour, the average output power stabilized at about 65.4 W. Note that there were periodic power fluctuations, due to the slow variation of the polarization state of the non-PM fiber seed oscillator. In a non-PM fiber, the state of the polarization is sensitive to the fiber birefringence which varies with temperature, pressure, and mechanical disturbances [26, 27]. The periodic variation (~ 1.8 min) of the polarization state is likely to result from the periodic temperature fluctuation of the water chiller. One solution to the power fluctuations is to substitute the seed laser with an all-PM fiber oscillator.
- The diamond Raman resonator consisted of two plano-concave mirrors as the input coupler and output coupler, respectively. The input coupler with 50 mm radius curvature was highly transmissive ($>98\%$) at 1,018 nm and highly reflective ($>99.9\%$) at 1,178 nm. The OC had a 100-mm radius of curvature, was highly reflective ($>99.9\%$) at 1,018 nm, and provided approximately 0.1% transmission at 1,178 nm. The diamond (Element Six Ltd., low-birefringence, low-nitrogen, CVD-grown single crystal) with dimensions of 8 mm \times 4 mm \times 1.2 mm was inserted at the waist of the near-concentric resonator.

The output power of 1,178 nm Stokes is plotted in **Figure 2B** as a function of the incident 1,018 nm pump power. The threshold was 9.3 W, beyond which the 1,178 nm output only attained power of 6.1 W at the incident pump power of 63 W since the transmittance of the OC at 1,178 nm was only 0.1%. The effective Raman gain coefficient g_{eff} is proportional to $g_0 \omega_R / (\omega_R + \omega_p + \omega)$, where g_0 is the Raman gain coefficient, and ω_R , ω_p , and ω are the FWHM linewidths of Raman gain

profile, pump, and Stokes, respectively [28]. Therefore, a pump with much narrower linewidth than Raman gain profile (e.g., $\omega_p \ll 45$ GHz) is required to achieve a highly effective Raman gain coefficient. In order to further investigate the impact of pump linewidth on effective Raman gain and thus the threshold of diamond Raman laser, a second pump laser with a linewidth of 20 GHz was employed. The calculated g_{eff} for a pump linewidth of 7.8 GHz is approximately 16% higher than for a 20 GHz pump, assuming that ω_R is 45 GHz and Stokes linewidth of ω is neglected at threshold. The laser threshold for the broad bandwidth laser was 11.4 W and 22.5% higher than that for the 7.8 GHz pump.

- The beam profiles of pump and Stokes at maximum power are included in **Figure 2B**, which depicts an evidence of beam cleaning during stimulated Raman scattering in diamond [29]. **Figure 3B** shows the evolution of Stokes output spectrum through SLM to multi-longitudinal modes with the increasing of pump power due to the thermal drift in cavity length and nonlinear spectral broadening. Those spectra were measured by using a cavity mode-spacing resolved spectrometer (HF-8997-2, LightMachinery). **Figure 3B** shows an SLM spectrum with an output power of 0.6 W at the pump power 13 W, and the FWHM bandwidth is 0.8 GHz, which is the limitation of the spectrometer resolution. At the highest output power of 6.1 W, a multi-longitudinal mode Stokes spectrum was observed with a Lorentzian FWHM linewidth of 13.6 GHz, as shown in **Figure 3C**.

CONCLUSION

In summary, a high-power linearly polarized 1,018 nm fiber laser with 7.8 GHz linewidth is demonstrated based on a pair of narrow-bandwidth FBGs. The highest output power was 75 W, corresponding to an optical efficiency of 64%, and the spectral

trace had a contrast of approximately 49 dB against the noise floor. One of the important applications for a narrow-linewidth 1,018 nm laser is to pump a diamond Raman laser for generating the first-order Stokes at 1,178 nm which can be frequency doubled to 589 nm for a sodium guide star laser. Here, the 1,018 nm fiber laser was successfully utilized in a standing-wave diamond Raman cavity to generate a power of 6.1 W and near-diffraction limit 1,178 nm output. And the spectral evolution of Stokes from a single mode to multimodes with the increase of pump power was observed.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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