Breakthrough of Kilowatt-Class 1178 Nm Narrow-Linewidth Fiber Amplifiers *Via* Cascaded Yb-Raman Hybrid Gains

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High-power narrow-linewidth 1178 nm fiber laser enables stable 589 nm emission through precise frequency-doubling effect, offering a robust technical pathway to fulfill the critical requirements of sodium laser guide star systems that demand both spectral purity and power stability for atmospheric turbulence compensation. Yb-doped fiber amplifiers (YDFAs) and Raman fiber amplifiers (RFAs) are the two typical configurations to achieve narrow-linewidth laser sources at 1178 nm. However, the output power of narrow-linewidth YDFAs and RFAs at 1178 nm is currently remained at hundred-watt class. In the last decade, a new insight of Yb-Raman fiber amplifiers (YRFAs) has been proposed to obtain high-power fiber lasers at wavelengths above 1100 nm, which combines the advantages of YDFAs and RFAs in balancing the amplified spontaneous emission (ASE) and nonlinear effects. Nevertheless, in the YRFA systems, the pump noise transfer induced spectral broadening diminishes the advantage of this strategy in realizing high-power narrow-linewidth fiber lasers with wavelength ranging from 1100–1200 nm. Recently, our theoretical analysis demonstrated that the narrow-linewidth property of the seed laser can be well maintained in YRFAs by designing a temporal-stabilized Raman-signal laser. This theory has been further verified in the single-stage Yb-Raman hybrid gain system, and beyond kilowatt-level narrow-linewidth YRFA is achieved at the wavelength of 1120 nm. Considering the limited wavelength expansion capability of the single-stage ytterbium Raman hybrid gain technique, we proposed and validate the capacity of a cascaded Yb-Raman hybrid gain technique in achieving high-power narrow-linewidth lasers with longer wavelengths.

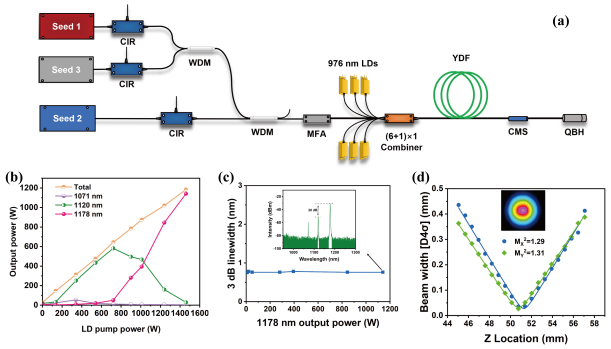

Figure 1: Experiment setup and results. (a) Experimental setup of the kilowatt 1178 nm fiber amplifier; (b) power curves; (c) linewidth curves. Inset: output spectrum; (d) beam quality (M2)

In this work, we demonstrate a breakthrough of a kilowatt-class 1178 nm narrow-linewidth fiber laser, which is based on the cascaded Yb-Raman hybrid gain technique. Fig. 1(a) illustrates the cascaded YRFA system configuration, which comprises three phase-modulated single-frequency fiber lasers operating at 1071 nm, 1120 nm, and 1178 nm. The 1071 nm seed laser, amplified by Yb-ion gain, serves as a temporally stable first-stage Raman pump to amplify the 1120 nm laser, which subsequently acts as the second-stage Raman pump to amplify the 1178 nm laser, ultimately enabling high-power, narrow-linewidth output laser at 1178 nm. Fig. 1(b) demonstrates the power evolution trends in the cascaded YRFA. Benefited from the cascade Yb-Raman hybrid gain technique, the output laser realizes Raman energy transfer from 1071 nm to 1120 nm and finally to 1178 nm. At the maximum output power (1.18 kW), the powers share of the lasers at 1071, 1120, and 1178 nm are calculated to be 0.9, 2.5, and 96.6%, respectively. Fig. 1(c) illustrates the 3 dB linewidth of the laser at 1178 nm during the amplification process, which is well maintained at ∼0.76 nm. The inset of Fig. 1(c) displays the output spectrum at maximum output power. The higher-order stimulated Raman scattering is not observed in the output spectrum, and the spectral peak at 1178 nm is ∼20 dB higher than that at 1120 nm. At the maximum output power, the beam quality of the output laser is measured with Mx2 = 1.29 and My2 = 1.31, as shown in Fig. 1(d).

In conclusion, the experimental results validate the superiority of cascaded Yb-Raman hybrid gains with temporally stable pumping for achieving kilowatt-level narrow-linewidth all-fiber amplifiers at the long wavelength extreme of the Yb gain spectrum. The obtained high-power narrow-linewidth fiber laser is possible to provide a high-brightness laser source for the development of a sodium laser guide star system.