670 W Single-frequency Retrievable Multi-tone All-fiber MOPA

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Abstract— We demonstrated a single-frequency retrievable multi-tone all-fiber laser in master-oscillator power-amplification (MOPA) configuration with the highest recorded power of 670 W. The seed laser runs in multi-tone regime by phase modulating a single-frequency fiber laser using a sine wave signal. Power amplification of the multi-tone master oscillator is then implemented by four cascaded all-fiber power amplifier and a power scaling up to 670 W is achieved. A proof-of-concept experiment for retrieving single-frequency laser from the high power multi-tone laser is carried out by implementing a demodulation signal, which is π phase shift of the modulation signal, on the output laser at a relative low power level. Results indicated that the single-frequency laser can be retrieved with a sideband suppression of more than 20 dB at the power level of 670 W. This method may provide a feasible way for power scaling of single-frequency laser over the SBS limitation in fiber amplifier.

1. INTRODUCTION

High-power single-frequency fiber lasers are widely used in a lot of fields, including nonlinear frequency conversion, remote sensing and coherent beam combining [1, 2]. Nevertheless, restricted in terms of thermal load, fiber damage and nonlinear effects, especially the stimulated Brillouin scattering (SBS) effects [3], the ultimate output power of the single-frequency fiber amplifier has been limited to the several hundred watts level [4, 5]. Moreover, the highest reported single-frequency all-fiber laser is about 203 W [6]. In order to suppress SBS and increase the output power in fiber amplifier, various techniques for SBS suppression, including stress, large-mode area (LMA) fibers, thermal gradients [7] and gain competition [6] have been proposed. Broadband linewidth [8] and multi-tone single-frequency [3, 9] master oscillator is also helpful for SBS suppression. But the linewidth is somewhat broad in a lot of applications such as coherent beam combining. Special assistant technique (such as fine optical path control using optical delay line in coherent beam combining) should be implemented and the system becomes bulk and complex. If the amplified broadband linewidth laser could be converted back to be a single-frequency one, high power single-frequency laser over the SBS limitation would be achieved. There are a lot of solutions to get broadband or multi-tone single-frequency master oscillator, such as built a broadband linewidth laser, generating broadband linewidth laser by phase modulation with a noise signal [10], or a regular signal [11]. Of the three methods mentioned above, modulating the single-frequency laser by a sine wave signal is a simple way. Furthermore, this type of broadband linewidth laser is multi-tone one and can be converted to single-frequency laser by a special demodulation signal [12]. In previous work, Rhein et al. [11] has demodulated an amplified phase modulated single-frequency signal laser at the power of 10 W. Here in this paper, we will report our experiment demonstration of a 670 W single-frequency retrievable multi-tone amplifier. Experiment for retrieving single-frequency laser from the high power multi-tone laser is carried out by implement a demodulation signal has a π phase shift of the modulation signal on the output laser. Results indicated that the single-frequency laser can be retrieved with sideband suppression by more than 13 dB at the power level of 670 W. The feasibility of demodulation a phase modulated single-frequency laser in high power level is demonstrated.

2. EXPERIMENT SETUP

The experimental setup is shown in Fig. 1. A linearly polarized single-frequency laser generating 40 mW of power at a wavelength of 1064 nm with a linewidth of about 200 kHz [13] is phase modulated a modulator (PM1). A function generator (FG) which can produce sine wave signal is used to driven PM1. The multi-tone master oscillator (MO) is then amplified by a four stages power amplifier chain.

The first pre-amplifier (AI) is based on a single-mode Yb^{3+} doped fiber (YDF, core/cladding diameter 6/125 μm, 0.12 NA), which scale the seed laser from 10 mW to more than 200 mW. The second and third pre-amplifier are both based on double cladding YDF with core/inner diameter of 15/130 μm, 0.08/0.46 NA. In the second amplifier (AII), a 4 meter long YDF is pumped by a 9 W

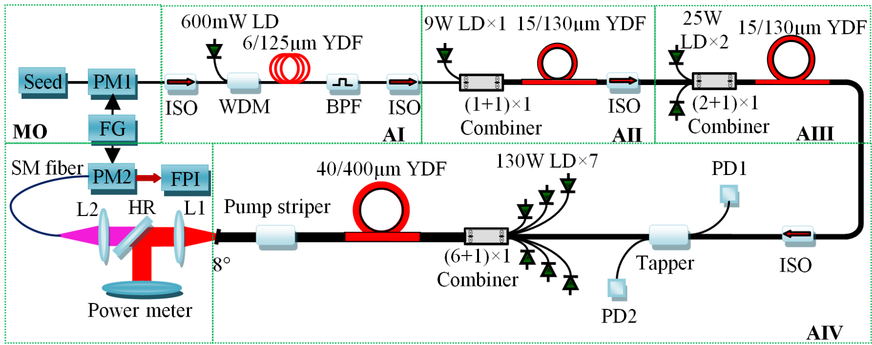


Figure 1: Experimental setup of the single-frequency retrievable fiber laser in MOPA configuration. PM1 and PM2-phase modulator, FG-function generator, ISO-isolator, WDM-wavelength division multiplexing, LD-laser diode; YDF-Yb^{3+} doped fiber, BPF-band pass filters, PD1 and PD2-photodetector, L1-collimated lens, HR-high reflection mirror, L2-focus lens, FPI-Fabry-Perot interferometer, AI, AII, AIII and AIV-amplifiers in different stages.

fiber pigtailed laser diode (LD) and scale the power up to 5 W. In third amplifier (AIII), a 6 meter long YDF is pumped by two 25 W LDs and can scale the power up to 30 W. The main amplifier bases on a $\sim$ 7.5 meter long LMA double clad YDF with core diameter of 40 μm ($NA = 0.06$), inner cladding diameter of 400 μm ($NA = 0.46$), absorption coefficient of $\sim$ 5.5 dB/m at 975 nm wavelength. Six 130 W multimode fiber pigtailed 976 nm LDs are coupled into the gain fiber through a $(6 + 1) \times 1$ signal/pump combiner. The output end of the delivery fiber is angle cleaved at 8° to suppress spurious lasing. Between the third pre-amplifier and the main power amplifier (AIV), a tap coupler cooperated with two photodetedtor (PD1, PD2) are used to detect the output power of the third amplifier and especially to monitor the backward signal of the main amplifier. A control circuit is built to protect devices by turning off power supply of LDs when nonlinear increasing of the backward signal is observed. As the power handle ability of the tap coupler is lower than 20 W, the third pre-amplifier is operated at a lower power of 15 W. The output laser is first collimated by a lens (L_1), and then reflected by a high reflection mirror (HR). The reflected beam which contains main power ($> 99\%$) of the laser is sent to a power meter. The transmitted beam that contains less than 1% power of the laser is first focused by a lens (L_2) with a focus lens of 150 mm, and then coupled into a single-mode (SM) fiber. The signal in the SM fiber is sent to a phase modulator (PM2) for demodulation. A Fabry-Perot interferometer (FPI) is located after PM2 to measure the linewidth of the laser in different case. When PM2 is driven by a signal which is π phase shift of the modulation one, single-frequency laser could be retrieved.

3. RESULTS AND ANALYSIS

In experiment, when the single-frequency laser $E(t) = E_0 e^{-j\omega_0 t}$ is phase modulated by a sine wave phase signal $\varphi_m(t) = \psi_0 \cos(\omega_m t)$, multi-tone signal with expression $E_{md}(t) = \sum_{n=-\infty}^{\infty} j^n J_n(\psi_0) e^{-j(\omega_0 + n\omega_m)t}$ will generate. In experiment, the single-frequency laser is modulated by a sine wave signal with a frequency of 100 MHz, amplitude of 5 V. When the first two pre-amplifier is work at the full power, the output power and backward power of the main amplifier changes with the pump power is measured and shown in Fig. 2. The output power reaches as high as 670 W at the limited pump power of 765 W, with a power efficiency of about 86%. The monitored maximum backward power is less than 0.6 W. As the single-frequency laser is broadened by the phase modulation, SBS effect is suppressed, therefore, there are no nonlinearly increasing is observed in the measured backward power even at the highest power. In experiment, we coiled the fiber with a diameter less than 10 cm and used high-index gel to strip the high-order mode as well as residual pump in inner cladding of the large mode fiber to make the amplifier working in the lower mode. The measured beam quality M_2 is about 1.7 when the output power is 670 W. The beam profile of the amplifier at the highest power level is also inserted in Fig. 2.

The output power spectrum at the highest power is measured and shown in Fig. 3. We can see that the residual pump light is 25 dB less than of the signal. No ASE (Amplified Spontaneous Emission) is observed, which indicates the output power of the main amplifier can be further

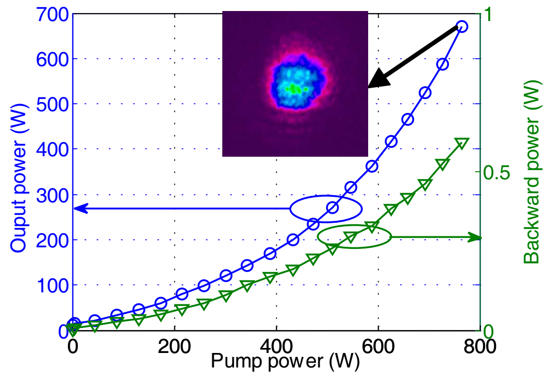


Figure 2: Output power and beam profile of the main amplifier in different pump power.

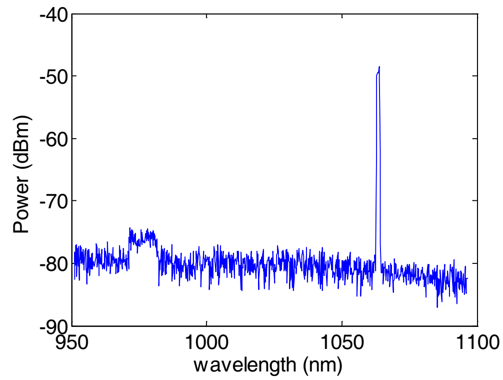
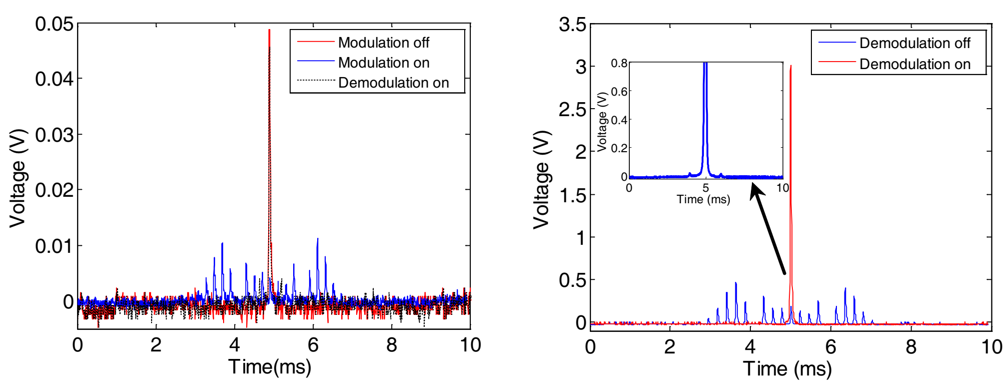


Figure 3: Spectrum of the main amplifier at 670 W output.

increased by only increase pump power.

To confirm the linewidth broadened and the feasibility of demodulation of the modulated single-frequency laser, we use an FPI (FPI100, FSR = 4 GHz, fineness $\sim$ 10 MHz, Toptica inc.) to measure the linewidth before and after the modulation and demodulation. Fig. 4(a) shows the measured linewidth before and after demodulation when the main power amplifier (AIV) is off. When the modulation is on, the single-frequency laser is broadened to be a multi-tone signal with a full measure linewidth of about 1.8 GHz. When the demodulation signal is on, a single-frequency like signal with only two sidebands are obtained with a side bands suppression of about 22 dB. When the main power amplifier is operated at the full power, the amplified signal is recorded and shown in Fig. 4(b), compared with Fig. 4(a), there is no obvious difference between before and after the main power amplifier. When the demodulation signal is applied, the retrieved single-frequency laser in full power operation is also generated with a sideband suppression of more than 20 dB. The residual demodulation error can be mainly attributed to the mismatch of the frequency, phase and amplitude between the modulation and demodulation signal. In the demodulated signal, only two sidebands are measured, which validated that the amplitude of the generated full wave mixing (FWM) is so small that it can't be recorded by the FPI. In multi-tone amplifier, FWM may appear, but as the power is much less than the signal power in each tone, the influence on the frequency retrieving can be neglected, this will be studied in theory latter.



(a) (b)

Figure 4: Oscilloscope trace of the over a Fabry-Perot interferometer (a) without and (b) with main power amplifier.

In theory, the power of the FWM sideband (with frequency of $\omega_{pps} = 2\omega_p - \omega_s$) produced by pump laser (with frequency of ω_p) and signal laser (with frequency of ω_p) can be calculated by $P_{PPS} = \eta\gamma^2 P_p P_s^2 L_{eff}^2$ [14–16]. Here η is conversion efficiency, for a signal positioned close to the pump, $\eta = 1$ [15]. P_p, P_s are the powers of pump and signal laser. γ is the nonlinear parameter, it can be calculated as $\gamma = n_2\omega/(cA_{eff}) = 2\pi n_2/(\lambda A_{eff})$ [17]. Here n_2 is the nonlinear index coefficient, λ is the wavelength of the laser and A_{eff} is the effective core area of the fiber. L_{eff} is the effective interaction length [17]. For a Silicon-based fiber, $n_2 = 3 \times 10^{20}\,\mathrm{m^2/W}$ at the wavelength of 1.064 μm [17]. In our experiment, the core diameter of the fiber is 40 μm, then γ is calculated to be $\gamma = 2.5 \times 10^{-4}\,\mathrm{m^{-1}W^{-1}}$. There is 7.5 m active fiber delivery a non-uniform power and a 0.5 m passive fiber delivery a power up to 670 W. The effective interaction length at the full power of 670 W can be estimated to be less than 3 m. In experiment, there are 17 sidebands amplifier (see Fig. 5(a)) which contains a total power of 670 W, therefore the minimum power of the lowest signal is calculated to be 1.5 W. The FWM sidebands can be calculated and shown in Fig. 5(b), the maximum power of the FWM sideband is less than 0.25 W, and the total power of the 61 FWM sidebands is less than 7 W. In Fig. 4(b), a voltage of 3.0 V represent a power of 670 W, therefore, the maximum response voltage of FWM sideband in the FPI is less than 1.1 mV, which can't be recorded effectively by the oscillograph. To conclude, the influence of the FWM sidebands on the single-frequency retrieving can be neglected.

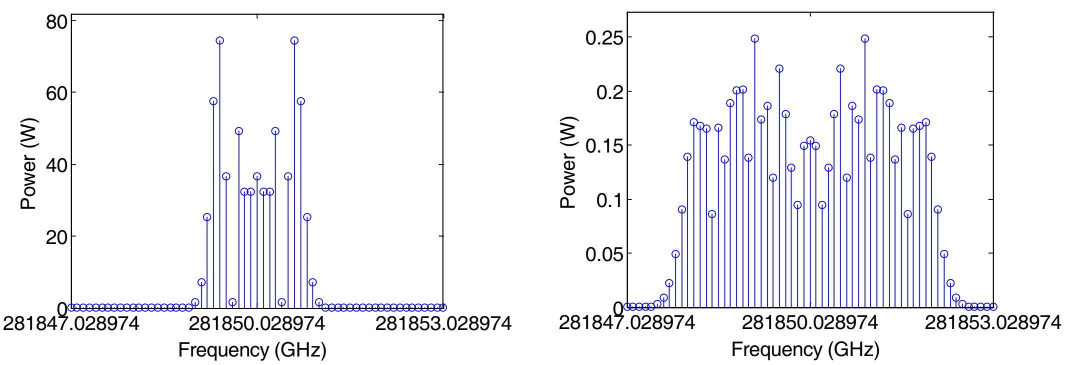


Figure 5: (a) Estimated power distribution and (b) FWM sidebands in amplifier.

4. SUMMARY

In conclusion, we have demonstrated a single-frequency retrievable laser with a record power of 670 W. The full linewidth is less than 1.8 GHz, and it's possible to be converted back to a single-frequency laser. Compared a with 25 GHz broad linewidth [18], this laser can be used for coherent beam combining directly without phase demodulation. It is should be note that we didn't retrieve single-frequency laser in a high power level for the damage threshold of the available phase modulator is less than 100 mW. Up to now, the damage threshold of commercially available free space KTP phase modulator is $20\,\mathrm{W/mm^2}$ [19], the power handle ability of this type of phase modulator is about 60 W. Although high power (up to 600 W) phase modulator is not available yet, as the development of material and relative technology such as resonant phase modulator [19], we believe that high threshold, high bandwidth and relative low half-wave voltage phase modulator will be available in the future. Therefore, if a high power phase modulator is available, a single-frequency laser with much higher power than that of so far reported can be retrieved. This may be a feasible way for power scaling up of single-frequency laser over the SBS limitation in fiber amplifier.

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