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ACTIVE PHASE LOCKING OF FIBER AMPLIFIERS WITH 180 GHZ ULTRABROAD LINEWIDTH

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Abstract—A fiber laser with 180 GHz ultrabroad linewidth is developed using a broadband light source and a bandpass filter. Active phase locking of two fiber amplifiers with 180 GHz linewidth is successfully realized using stochastic parallel gradient descent technique. The fringe contrast of the interference pattern is as high as 65% when active phase control is implemented. The reported results indicate a promising power scalability of fiber amplifier modules developed for phase locking.

1. INTRODUCTION

Phase-locked fiber laser/amplifiers can increase the output power while simultaneously maintaining good beam quality. Main technique approaches of phase locking can be classified into two categories: passive phasing without external control of optical phase [1–6] and active phasing in MOPA (master oscillator power amplifier) configuration [7–11]. For example, Lei et al. have reported a passively phase locked erbium-doped fiber ring lasers by using a common ring filter [6]. In MOPA configuration, single-frequency seed laser had been considered to be indispensable to improve the spatial coherence property and obtain a high brightness in the far-field [12, 13]. Our group has reported an efficient active phase locking system and two single-frequency laser amplifiers have been successfully phase locked [7]. Nevertheless, a strong amplified single-frequency signal in the fiber can generate an acoustic wave traveling in the same direction as the amplified signal. The interaction between the acoustic wave and the signal, known as Stimulated Brillouin Scattering (SBS), in turn

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generates the Stokes wave with a slightly lower optical frequency traveling in the backward direction that, which impose a serious limit on the output power [14, 15]. Single-frequency radiation makes the high-power operations of fiber amplifier more challenging due to low SBS threshold. The maximal output power of single-frequency fiber amplifier is limited to hundred watt level for many years.

The output power of fiber amplifier can be significantly improved by employing multi-tone seed laser [16, 17] or by broadening the bandwidth of seed laser broad enough when compared with the Brillouin linewidth ($\sim$ 50–100 MHz) [18, 19]. Recently, there comes up breaking news focus on kilo-watt level fiber amplifiers suitable for phase locking, where electro-optic modulator is employed to broaden the kHz level laser linewidth of a single-frequency fiber laser into several GHz to suppress the SBS effect. For the time being, commercial high power fiber amplifier with GHz-level-linewidth is available [20–22]. It is to be noted that in that technique approach, the single-frequency seed laser, electro-optic modulator and its driver are all expensive elements, which brings a significant increase in system cost. On the other hand, filter the light spectrum from an amplified spontaneous mission (ASE) seed source provides a simple and economical solution to provide a broadened linewidth, and the phase noise of fiber amplifier with 60 GHz linewidth had been measured using this technique [11]. In this manuscript, we will present active phase locking of fiber amplifiers with 180 GHz linewidth. The ASE seed source is constructed based on a broadband light source using double-pass bi-directional pump configuration, and the ASE is filtered by a bandpass filter (BPF) that provides 180 GHz linewidth. To the best of our knowledge, this is active phase locking of the broadest linewidth fiber amplifier endeavors that had been reported.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Figure 1. The laser used to seed the fiber amplifier with ultrabroad linewidth is self-made broadband light source. The pump source is a semiconductor (LD) laser with a central wavelength of 974 nm. The pump power is equally split using a fiber splitter (PS) to bi-directional pump the 10-meter-long Eribum-doped fiber (EDF). The reflection mirror is a broadband 3 dB coupler (CP) with two ports fusion spliced. The point A and B denoted in the subfigure represents the place where the optical power and spectrum is to be measured. The ASE is filtered by a specially designed BPF with a maximal power handing capability of 500 mW. The filtered ASE is then split into two channels using a 3 dB coupler; each channel is coupled to two $LiNbO_3$ phase modulators. The laser beams from the phase modulators are sent into Eribum-doped fiber amplifier (EDFA) to boost the laser power and then sent into pigtailed collimators. The laser beam is collimated via the collimator and then sent into free-space.

Tilt angle of the laser beams are carefully tuned to ensure the laser beams overlap with each other at the observing plane. The collimated output beam array is sampled by a mirror. After the mirror, part of the beam is sent to a home-made pinhole with a radius of 50 μm, a photoelectric detector is located immediately behind the pinhole. The location of the pinhole is carefully adjusted to ensure the maximum output signal of the detector. In this way, the central portion of the main-lobe can be imaged into the detector after passing through the pinhole. The optical power detected by the photoelectric detector is

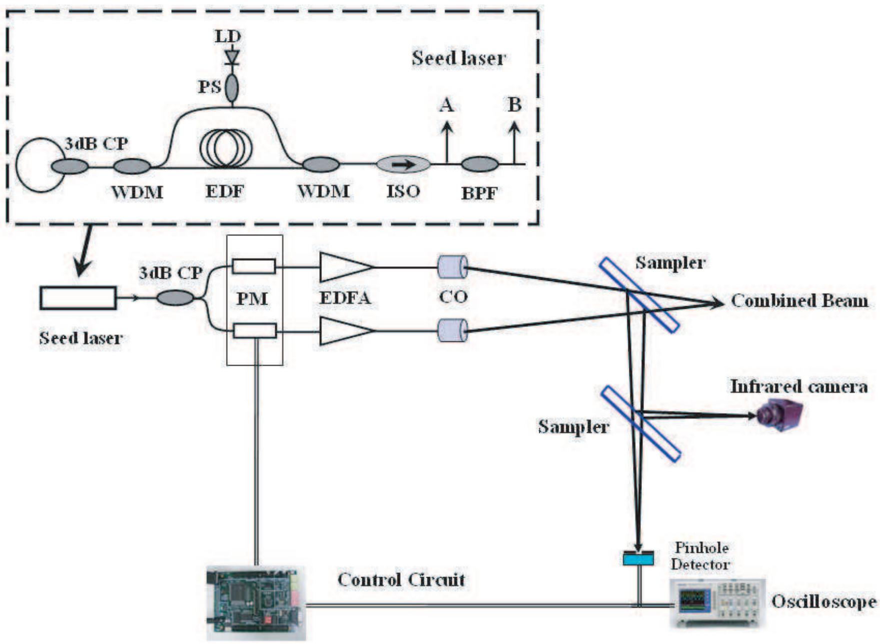

Figure 1. Experimental setup for phase locking of ultrabroad linewidth fiber amplifiers. LD: 974 nm pump laser diodes. PS: Power splitter. WDM: Wavelength-division multiplexer; EDF: Erbium doped fiber. CP: Coupler. ISO: Isolator. BPF: Bandpass filter. PM: Phase modulator. EDFA: Erbium doped fiber amplifier. CO: Collimator. A and B: The points where the laser power and spectrum is to be measured.

defined as the cost function of the stochastic parallel gradient descent (SPGD) algorithm [23]. Another part of the beam after the sampler is sent to an infrared camera to diagnose the profile of the combined beam. In our experiment, SPGD algorithm is performed on digital signal processor (DSP) and phase control signals are sent to the phase modulators through D/A converters and active phase control on each channel is thus implemented.

3. EXPERIMENTAL RESULTS AND ANALYSIS

In the experiment, the ASE power is measured to be 98 mW when the pump current of the LD is 500 mA (corresponds to 280 mW pump power), the pump conversion efficiency is about 35%. The ASE power is filtered to be 1.05 mW after passing the BPF. The maximal output power of each fiber amplifier is 30 mW. The ASE spectrum measured

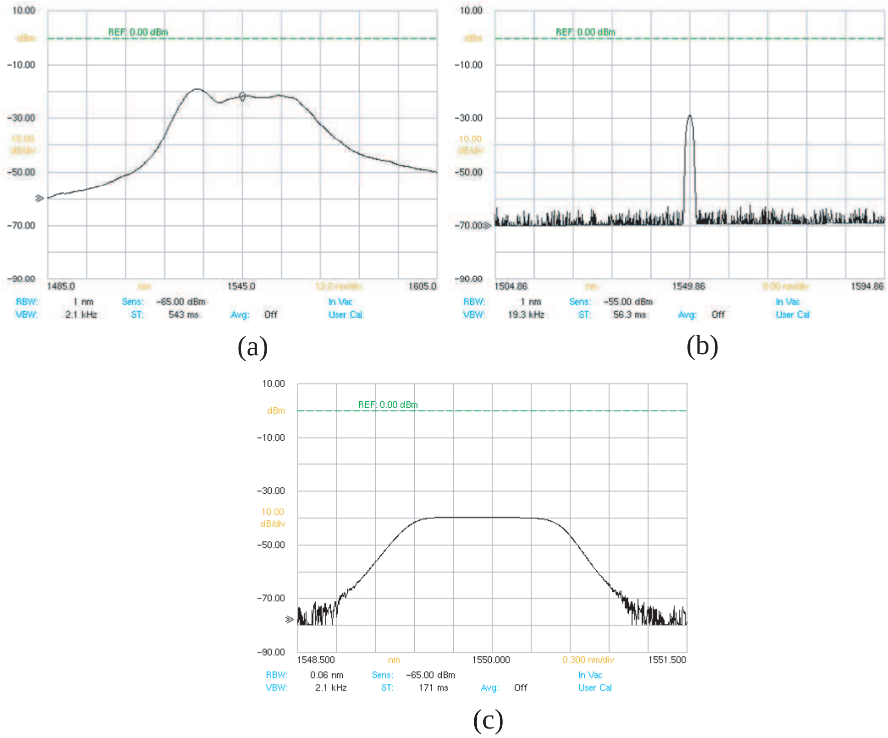

Figure 2. Optical spectrums. (a) ASE spectrum. (b) Filtered ASE spectrum. (c) Enlarged version of (b).

at point A (see Figure 1) by Agilent 86142B optical spectrum analyzer is shown in Figure 2(a), and the spectrum measured at point B (see Figure 1) is shown in Figures 2(b) and (c). It can be seen that the ASE spectrum is efficiently filtered to be a flat-topped shaped one, the 10 dB bandwidth is 1.5 nm (corresponds to a linewidth of about 180 GHz). The broad linewidth leads to the coherence length of the light is only a few millimeters and the requirement that the lengths of all the fiber channels must be matched in length to within a few millimeters. This issue is solved firstly by carefully cutting and fusion splicing of the fibers when building the whole system, and then after sending into free-space via collimators, free-space delay is performed in each channel in order to match the path lengths.

When all the seed laser and fiber amplifier are turned on, the whole system is in open-loop and the SPGD algorithm is not implemented, the power encircled in the target-pinhole fluctuates and the intensity pattern at the observing plane keeps shifting due to phase fluctuations in each fiber channel. The long-exposure far-field intensity distribution in 1-minute measuring time (the frame rate of the camera is 16 fps per second and a total number of 960 images are averaged) is shown in Figure 3(a). When SPGD algorithm is implemented and the whole system is in closed-loop, the intensity pattern at the observing plane is clear and steady and the long-exposure far-field intensity distribution in 1-minute measuring time is shown in Figure 3(b). By digital processing the image profile grabbed by the camera, the contrast of the coherent combined beam profile shown in Figure 3(b) is calculated to be more than 65%, where the fringe contrast is defined

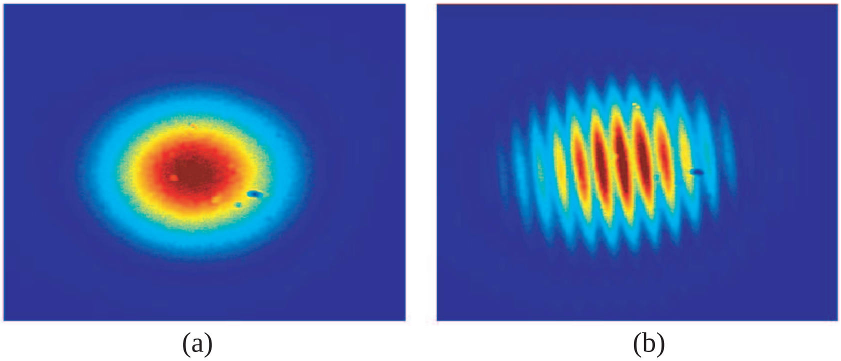

Figure 3. Long-exposure far-field intensity distributions: (a) Open loop without active phase control; (b) Close loop with active phase control.

by $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ and $I_{\min}$ are the maximum optical intensity and the adjacent minimum on the intensity pattern, respectively.

4. CONCLUSION

In summary, we have demonstrated active phase locking of fiber amplifiers with 180 GHz linewidth. According to the analysis presented in [24], 180 GHz linewidth is broad enough compared to the Brillouin linewidth ($\sim$ 50–100 MHz), so SBS effect can be efficiently suppressed, and the laser output power can be easily scaled to multi-kilowatt level. The results in this paper indicate that the output power of fiber amplifier modules developed for phase-locked laser array can be significantly improved because of mitigated SBS effect.

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