ns and fs Fiber Lasers
(Invited Paper)

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ABSTRACT: Pulse shaping technology is present to mitigate pulse narrowing and SBS effects in high energy/power ns fiber lasers and to balance SPM and gain narrowing in high energy/power fs fiber lasers.

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1. Introduction

High energy pulsed fiber lasers have been considered to be an enabling technology to many applications such as Lidar, free space communications, and material processing [1-13]. In eye safer Lidar applications, 200 ns pulse width is required. However, due to gain narrowing effects and SBS nonlinear effects in high power and high energy fiber laser, the energy extraction is limited and the pulse shape is distorted. In this paper, a special pulse shaping fiber laser will be discussed with over 1 W average power operation and 0.15 mJ pulse energy at a wavelength of 1550 nm and with a pulse width of 200 ns.

Ultrafast fiber lasers have been evolved into a new era for replacing solid-state ultrafast lasers and exploring new unprecedented applications. Close to kW and mJ level operation for fiber amplifiers have been demonstrated [10,11]. However, those demonstrations involved many solid state components such as solid state seed oscillator and free space grating stretcher and practically are hard to be robust systems. This paper also presents a breakthrough approach by introducing a simple MHz seed fiber oscillator to generate MHz signal pulses and PCF amplifier system to scale the power and energy. It completely eliminates a pulse picker and reduces significantly the complexity and cost of the high energy fs fiber laser system. 100 W output power and 100 micro-Joule were achieved with a pulse width at 600 fs.

2. Experiment on ns Pulse Shaping Fiber Lasers

We have successfully developed the driver for driving a laser at 1550 nm to achieve any wave format and pulse width for pulse generation. We can generate muti-micro pulses in one macro-pulse. This achievement provides us with the capability for high energy pulse amplification at 1550 nm in mitigating both SBS effects (by shaping micro-pulse) and gain narrowing effects (by shaping macro-pulse).

Assuming a full-width at half maximum (FWHM) Brillouin linewidth, $\Delta\nu_{SBS}$ = 13 MHz at 1.5 μm, the dephasing time, $T_2 \approx$ 20 ns, can be calculated from the relation:

$$T_2 = 1/(\pi\nu_{SBS}) \qquad (1)$$

T_2 describes the required time to phase the created phonons, which establishes the macroscopic acoustic wave in the material. For pulse widths less than T_2, the SBS gain is significantly reduced.

Figure 1 shows experimental results for an amplifier with LMA double cladding Er-doped fibers (EDF). The core diameter size is 17 micron. It is taken from the circulator port 3 (backward SBS). In Figure 2, the backward SBS generation clearly shows a threshold for exponential growth. Exponential growth was observed as the amplifier's pump level increased. Seed laser was operated at 10 kHz repetition rate and square shape pulses were generated. The pulsed width (FWHM) varies from 20 ns to 200 ns. Since SBS gain is proportional to laser's intensity, we presented in Figure 2A the SBS power as a function of peak power. The SBS power as a function of pulse energy was also plotted as a reference in Figure 2B. The SBS threshold increases clearly for shorter pulse widths. When the pulse width is 20 ns, which is close to the dephasing time T_2, SBS is significantly suppressed.

Another important phenomena was observed is that the pulse was compressed significantly when it evolves through the amplification stage. A 200 ns pulse width was compressed down to 10 ns at high energy level. This is partially due to the gain dynamics and partially due to the soliton formation in the anomalous dispersion fiber at 1550 nm. The 200 ns pulse evolution at different pump currents was tested. The seed macro-pulse width is 210 ns, the output pulse width reduces to 150 ns, 50 ns and 15 ns at 1A, 4A and 7A pump current respectively. By manipulating the macro pulse shape launched into the amplifier, the pulse narrowing issue can be resolved.

We generated 200 ns pulses at the output of the high energy amplifier at various pump currents and repetition rates. The pump current was tuned from 0 to 8.6 A and the repetition rate varied from 10 kHz to 100 kHz. The relationship between pump power and pump current is characterized. Because of the phenomena of pulse narrowing during the power amplification, we manipulate seed macro-pulse shape for each amplifying condition to maintain the square shape and ~200 ns pulse width of output pulses (as shown in Figure 2). The micro-pulse width is controlled at 20 ns. Output power and spectrum were measured in our experiment. The output power as a function of pump current and the output pulse energy as a function of current is plotted. The output powers were almost the same at different repetition rates ranging from 10 kHz to 100 kHz. The power was linearly increased with pump current. The optical efficiency for the power amplifier is about 10%. Higher pulse energy is obtained at lower repetition rate. The maximum pulse energy of 0.15 mJ was obtained at 10 kHz repetition rate and 8.6A pump current. No SBS is observed. A prototype is developed and delivered.

3. Experiment on fs Pulse Shaping Fiber Lasers

Ultrafast fiber lasers, by definition, should be all fiber based laser system or with minimum non-fiber based components. At lease the seed laser, stretcher, amplifiers should be fiber based [12,13]. Those lasers using only one or two pieces of fibers in the amplifier stages should not be counted as fiber lasers. The progress in this direction is critical to practical industrial applications by providing compact, robust and cost effective solutions. Up to 100 micro-J has been developed into product by using a pulse picker method. However, due to the nonlinearity, gain narrowing, and third order dispersion (TOD) mismatch, the pulse width is limited to sub-ps level. Moreover, the high price is limited for this pulse picker approach to be deployed widely.

In our experiment, 1 MHz all fiber seed oscillator in direct generation of 1 MHz mode locked pulses. We also used a novel fiber-based dispersion management stretcher (patents 7,430224, 7430, 226, and 7,440,173) in dechirping the pulse and reducing TOD to the minimum. One of the key pulse-shaping techniques is to manipulate the third-order dispersion (TOD) of the fiber. Basically, the dispersion in the fiber is controlled by both material dispersion and waveguide dispersion. In the 1020–1090 nm spectral region, material dispersion shows a positive dispersion slope. With traditional fiber designs such as that for Corning's (Corning, NY) SMF-28, the TOD is always a positive number around 0.3 ps/nm^2-km, which does not match the TOD of the grating compressor used. However, by manipulating the fiber waveguide structure (with a depressed cladding), waveguide dispersion can be introduced to modify the material dispersion such that the TOD and dispersion slope of the whole fiber system are matched and compensated, especially with the grating compressor.

Bulk grating pair was used as a compressor. If photonic bandgap fiber (PBF) can be used in the compression stage, a truly all fiber solution is provided for the high energy fiber laser without any discrete free space components. This is significant for many industrial applications.

In the high power PCF amplifier, firstly, a photonic crystal fiber (PCF) is used to provide large mode field diameter (60 μm) for signal amplification in the core and large numerical aperture (NA) as high as 0.8 in the cladding for coupling more pump power into the fiber. This enables the use of a short length of fiber to high average output power and to reduce the effect of nonlinearity for high energy pulse. Secondly, the PCF is highly doped so more power extraction can be accomplished. Figure 1 shows detailed design of the PCF high power amplifier with integrated pump solution. It has a total of 200 W pump power lauched into the PCF amplifier. An experiment at 100 micro-J level energy (100 W average power) with a pulse width < 600 fs has been demonstrated at a pulse repetition rate of 1 MHz (Figures 3 and 4) and with M2<1.3. The contrast ratio (peak voltage/valley voltage) is higher than 36 dB, which indicates very clean pulse amplification.

4. Discussion and Conclusion

In summary, we have demonstrated a pulse shaping technology to generate pulse shapes in any formats for ns pulsed fiber lasers. This technology is demonstrated to be an efficient way to mitigate SBS effects and pulse narrowing effects in high energy/power fiber lasers. We successfully generated a 200 ns seed macro-pulse with micro-pulses less than 20 ns. The micro-pulses generation allows us to suppress SBS significantly, thus dramatically increase the output energy limit. The macro pulse is shaped to be against the pulse narrowing effects. After power amplification, an average power of over 1 W and the pulse energy of over 0.15 mJ were obtained at 1550 nm. Excellent pulse shape, high extinction ratio and power stability were achieved. A reliable prototype was developed. To further increase the energy level, we have increased the energy to 0.5 mJ and average power to 5 W. The laser becomes instable due to SBS and 1 micron lasing. SBS reduction can be achieved by reducing the micro pulse width to less than 10 ns. More development effort is needed to suppress the 1 micron lasing.

We have also demonstrated a 100 W 600 fs MHz fs fiber laser with all integrated fiber optics components other than compressor and eliminated pulse picker for reduction of system complexity and cost. This demonstration can be readily converted to a product by minimum engineering. By adding another stage of amplifier, kW level of output power can be expected.

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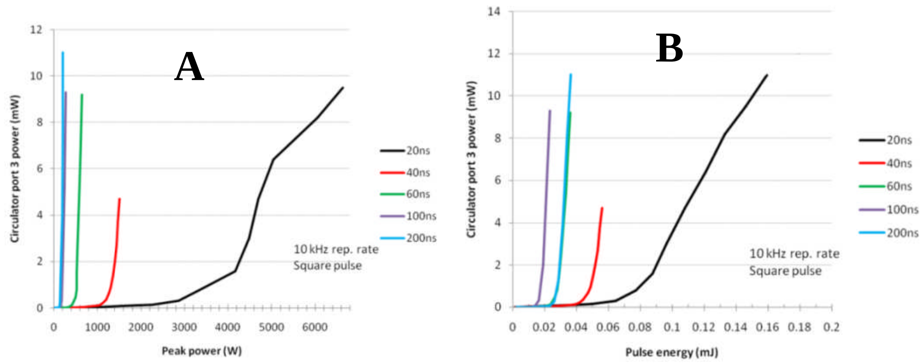

Figure 1 SBS Power (from Circulator Port 3) as a functions of: A) Output peak power; B) Output pulse energy.

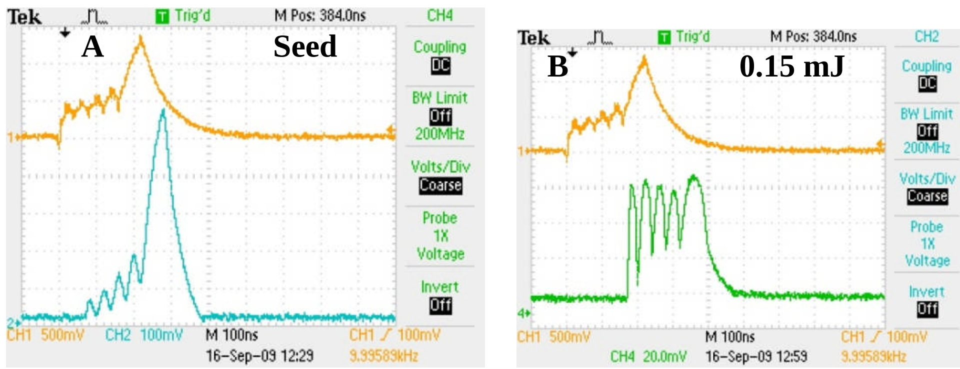

Figure 2 Manipulating seed pulse shape to generate ~200 ns amplified pulses. A) Seed shape; B) At 0.15 mJ (8.6 A), ~200 ns macro-pulse width with flat top was obtained.

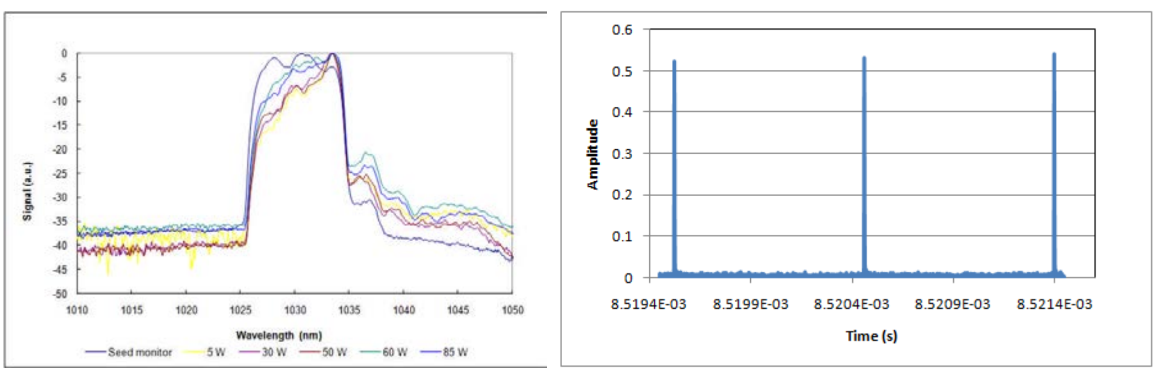

Figure 3 Spectra and pulse train of MHz high power/energy fs fiber laser

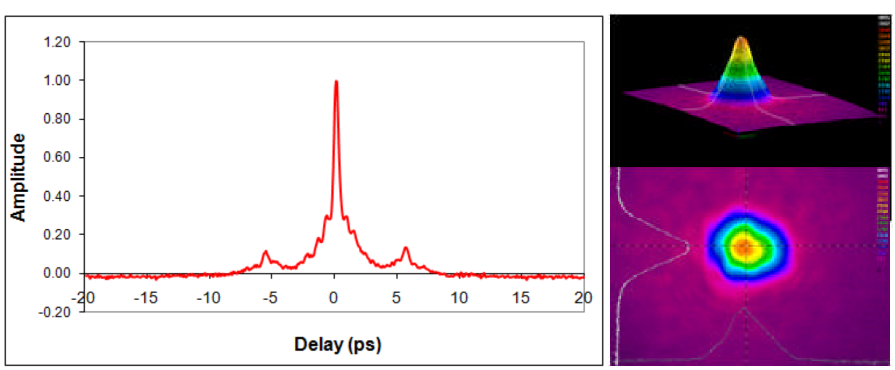

Figure 4 Pulse train and beam profile for 100 W and 100 micro-J operation. The satellite pulse comes with the nonperfect PM PCF fiber design (PM: polarization maintaining).