Pulse shaping high-energy fiber lasers

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Manipulating the pulse shape of a laser as it is launched into an amplifier mitigates distortion and scales up energy levels.

High-energy pulsed-fiber lasers represent an enabling technology for building the high-power transmitters required by future space communications and lidar (light detection and ranging) applications. In addition to high energy, light weight, and high wall-plug efficiency, the next generation of pulsed fiber lasers will need to possess features such as a superior extinction and optical signal-to-noise ratios. Finally, system performance over long distance depends on stable pulse shape to counteract attenuation, distortion, and delay. Especially at the eye-safer wavelength of 1550nm, high-energy fiber lasers face two challenges. One is stimulated Brillouin scattering (SBS), which limits peak-power handling because of narrow linewidth. The other challenge is the narrowing of pulse width during amplification, which further limits energy extraction and peak-power handling, and also contributes to SBS.

We have observed that as the pulse evolves through the amplification stage, it undergoes significant compression. A 200ns pulse width compresses down to 10ns at the highest energy level. This effect is mainly due to gain dynamics and partially also to soliton (a special kind of wave packet) formation in the anomalous dispersion fiber. Figure 1 shows pulse evolution at different pump powers. Further energy scaling can be achieved with pulse-shaping technology using large-mode-area, multimode, or photonic crystal fiber, any of which allows the large-mode field diameter to accommodate the high peak power and reduce SBS. Manipulating the pulse shape launched into the amplifier mitigates the pulse narrowing effect by compensating distortion at the leading edge of the pulse. In the experiment described here, we achieved an energy level of 0.13mJ at 1550nm while maintaining a 200ns pulse width and diffraction-limited beam quality.

SBS arises from the interaction between the optical field and acoustic phonons in the fiber. Although the material nonlinearity of silica fiber is actually not very high, the typically high optical intensity and long propagation length strongly favor nonlinear effects. At a high-enough input power, SBS will convert transmitted light in the fiber to a scattered, Stokes-shifted reflection (i.e., one that has lost vibrational energy). SBS poses the most stringent power limit for the amplification and passive propagation of narrow-band optical signals in fibers.

In a single-mode optical fiber, the Brillouin frequency shift is given by:

$$v_B = 2nV_s/\lambda,$$

where $V_s$ is the speed of sound in the medium, $n$ is the refractive index, and $\lambda$ is the wavelength. If we choose $V_s = 5460$m/s, $n = 1.5$ for glass, then we obtain the typical value of a Brillouin frequency shift in optical fiber at 1550nm of 10.5GHz (corresponding to a 0.084nm shift in wavelength).\(^1\) Assuming a full width at half-maximum Brillouin linewidth—$\Delta v_{\text{SBS}} = 13$MHz at 1.5$\mu$m—the dephasing time, $T_2 \approx 20$ns, can be calculated from the relation:

$$T_2 = 1/(\pi \Delta v_{\text{SBS}}).$$

$T_2$ describes the time required to phase the created phonons, which establishes the macroscopic acoustic wave in the material. For pulse widths less than $T_2$, SBS gain is significantly reduced. This provides a practical way of reducing SBS effects by

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manipulating the pulse width <20ns for micropulses. When a macropulse width is longer than 20ns, we can shape the pulse by including several micropulses (pulse width <20ns).

Figure 2 shows an example of the output of a 200ns amplified pulse with a flat top by manipulating the seed pulse shape for both macro- and micropulses. The seed macropulse shape is similar to a triangle. In one 200ns macropulse, the wave format is split into several narrower pulses to suppress SBS. Consequently, the new SBS threshold increases dramatically. After amplifying to the highest energy level, the output pulse width is 210ns with a flat top. Using this method, we have obtained diffraction-limited 0.13mJ pulse energy at a wavelength of 1550nm for 200ns pulses (without observing any obvious SBS effects or detriment to the pulse shape).

Pulse-shaping technology offers a vital solution in handling pulse distortion and SBS effects in high-energy amplifiers and fiber lasers. It has potential application in all types of fiber lasers, including ytterbium- and thulium-doped lasers. In future, we will be working to scale up the energy level to the millijoule range.

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References