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Exploitation of stimulated Raman scattering in short-pulse fiber amplifiers

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Abstract

Stimulated Raman scattering (SRS) generally limits the performance of short-pulse fiber amplifiers. We present the results of experiments that show that, under some conditions, SRS can extend the performance of amplifiers limited by nonlinear phase accumulation. The Stokes spectrum can be free of distortions arising from self-phase modulation and can circumvent the gain-narrowing limit of the amplifier. The generation of 1 μ J and 90 fs pulses from a single-mode fiber amplifier illustrates the potential of the process.

Nonlinear effects usually limit the generation and propagation of ultrashort light pulses. The small mode areas and long interaction lengths for light propagating in optical fiber lead to appreciable nonlinear effects for even modest pulse energies. Chirped-pulse amplification (CPA) is the primary approach to avoiding nonlinearity in short-pulse amplifiers. However, practical limits to the stretched-pulse duration imply that the maximum pulse energy is typically limited by the onset of nonlinear effects. The accumulation of excessive nonlinear phase shift through self-phase modulation (SPM) increases the duration and degrades the quality of the amplified and compressed pulse [1–3]. These effects occur for nonlinear phase shifts $\Phi^{\text{NL}} > 1$. Recent work has shown that $\Phi^{\text{NL}} \sim 10\pi$ can be tolerated in fiber amplifiers, through the use of spectrally shaped pulses [4] or compensation by third-order dispersion [5,6]. In principle, the effects of SPM can always be avoided by increased stretching. However, beyond a threshold peak power, the onset of stimulated Raman scattering (SRS) causes rapid growth of the Stokes-shifted wave and corresponding depletion of the original pulse. SRS transfers energy to wavelengths where the amplifier gain is reduced or nonexistent and, thus, becomes a loss.

Here we show that SRS can allow circumvention of the energy limits that arise from SPM. For each fiber CPA system, there will be a maximum amplified-pulse energy beyond which the pulse is distorted. At even higher energies, SRS will occur. We demonstrate that the generated Stokes pulse can be dechirped to nearly the transform limit, and its peak power can significantly exceed that obtained by CPA. Furthermore, the Stokes pulse avoids gain-narrowing of the spectrum, and is free from spectral modulations that may arise from nonlinear phase accumulation. Thus, SRS can offer benefits for femtosecond fiber amplifiers.

The experimental arrangement used to study SRS (Fig. 1) consists of a stretched-pulse fiber laser with a repetition rate of 44 MHz, a 200 m fiber stretcher, two amplifiers, a 20 m segment of fiber, and a grating compressor. All fiber is single-mode fiber (SMF), with 6 μ m

core diameter. Each amplifier is 0.5 m of highly doped Yb fiber. Between the amplifiers, the pulse repetition rate is reduced to 220 kHz by an acousto-optic modulator. Pulses from the oscillator are stretched to 110 ps duration, and amplified to 3 and 100 nJ energy in the first and second amplifiers, respectively. The gain of the second stage is limited to ~20 dB to avoid significant amplified spontaneous emission, and this determines the 100 nJ maximum pulse energy.

For the value of net third-order dispersion in this experiment, the maximum peak power will be obtained with $\Phi^{\text{NL}} \sim 4\pi$ [5,6]. This corresponds to a pulse energy of about 200 nJ in the amplifier. SRS in fiber was observed many years ago [7,8]. The threshold for SRS as calculated from the simple formula [9]

$$P_{\text{th}} \cong \frac{16A}{g_R Z_{\text{eff}}},$$

with A as the mode area, g_R as the Raman gain coefficient, and Z_{eff} as the effective gain length, is approximately 40 kW and corresponds to 4 μJ pulse energy; SRS is negligible in the amplifiers.

The amplified pulses are launched into 20 m of SMF, and typical output spectra are shown in Fig. 2. The 20 nJ pulse accumulates $\Phi^{\text{NL}} \sim 10\pi$ after propagation through the SMF and exhibits significant distortion upon dechirping, as expected. The estimated threshold for SRS in this fiber is 20 nJ. For pulse energies of up to ~60 nJ, fine structure on the initial spectrum grows but does not increase in frequency, which is expected for a highly chirped pulse that accumulates significant nonlinear phase. The first indications of SRS appear at 80 nJ. For total pulse energies between 80 and 100 nJ, the ripples on the spectrum continue to grow, and the center of the spectrum is depleted as the Stokes pulse grows. The bandwidth of the Stokes pulse is comparable to the pump bandwidth. A remarkable feature of the Stokes pulse is its smooth spectrum; it is completely free of the modulations of the original spectrum. This spectral-cleaning aspect of the SRS process has not been reported previously, to our knowledge. The temporal profile of the chirped pulse mimics the spectral shape, so the Raman response somehow filters the pulse structure. Theoretical modeling is needed to understand this process.

The evolution of pump and Stokes pulses in the presence of phase modulations and group-velocity mismatch has been studied theoretically [10], but the specific case of a highly chirped input pulse has not been presented. Reference [10] suggests that, for negligible pump depletion and temporal walk-off, the Stokes pulse may be compressible in this situation. Zhavoronkov *et al.* studied SRS of femtosecond pulses in a barium nitrate crystal, which has a vibrational mode at 1047 cm^{-1} with a dephasing time of 25 ps. Theory and experiments show that a linear chirp is transferred to the Stokes pulse under these conditions, which was, therefore, compressible from 250 ps to 190 fs [11]. No one has attempted to exploit this process in optical fiber, where the Raman gain is much lower and the vibrational linewidth much broader. The broad, smooth spectrum of the Stokes pulse, combined with a linear chirp, suggests that ultrashort Raman-shifted pulses may be obtained.

To follow the SRS process further requires higher energy or longer fiber lengths. We do find that the Stokes pulse continues to grow slowly with fiber lengths above 20 m. We added one more stage of amplification, along with 2 m of SMF (indicated by the dashed box in Fig. 1). The input to the amplifier is the 100 nJ spectrum of Fig. 2. The peak of the gain of Yb-doped SMF is near 1030 nm. Thus, the Stokes pulse, near 1080 nm, will not be amplified

efficiently in such a fiber. The output spectra after amplification to 200 and 360 nJ total energy and propagation through the 2 m fiber are also shown in Fig. 2. The Stokes pulse continues to grow, while the pump pulse continues to develop deep structure. The total energy can be increased to 2 μ J, at which point a second Stokes pulse begins to arise near 1140 nm. After filtering of the residual pump pulse [Fig. 3(a)], 1 μ J can be obtained in the Stokes pulse.

The 1 μ J Stokes pulse can be dechirped to 90 fs duration [Fig. 3(b)], close to the transform limit of the 23 nm bandwidth. This confirms that a nearly linear chirp was transferred from the original to the Stokes pulse. The peak power of the (chirped) Stokes pulse is at least five times the maximum peak power achievable by CPA with this combination of stretcher and SMF amplifier, without serious distortion of the dechirped pulse. The shortest pulse that can be obtained in linear CPA with Yb fiber is typically $\sim$ 120 fs, determined by gain-narrowing. Thus, the Raman process also provides a way to circumvent the gain-narrowing limit.

Second and third Stokes pulses are observed at around 1140 and 1200 nm, respectively (Fig. 4), in experiments performed with a separate apparatus. Experimentally, the bandwidth appears to grow significantly with Raman order (Fig. 4). The bandwidth of the third Raman order is already comparable to the Stokes shift between orders, which leads to substantial overlap with the second order. However, it may be possible to reach an $\sim$ 50 nm bandwidth, which corresponds to pulse duration below 50 fs at 1200 nm. The energy and chirp of the higher orders remain to be investigated.

To summarize the main points of this work, SRS can generate transform-limited pulses that can extend the usual limits of SPM in CPA. The energy of the Stokes pulse can exceed the maximum undistorted-pulse energy of an amplifier. The broadband Stokes pulse also provides a way to circumvent the gain-narrowing limit of ordinary amplification. Thus, higher energy and shorter pulses are possible. These features offer new degrees of freedom for optimizing the performance of femtosecond fiber amplifiers. Of course, if an application requires that the wavelength be that of the peak of the fiber gain, or if subsequent amplification in the same fiber is required, SRS will not be valuable, as it shifts the pulse away from the peak of the gain. However, for many applications, a shift of $\sim$ 40 nm will be inconsequential, and it is also possible to design fibers for peak gain at longer wavelengths. Successive amplification stages could be designed to amplify successive Stokes orders, for example. Additional theoretical and experimental work is needed to understand this process and then optimize it. Initial results presented here include the generation of 1 μ J pulses that can be dechirped to 90 fs duration from SMF, which is already remarkable.

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Fig. 1.

(Color online) Schematic of experimental setup. A_1 , A_2 , and A_3 are Yb-doped fiber amplifiers. AOM, acousto-optic modulator; ISO, isolator; SMF_1 is the 200 m stretcher; SMF_2 and SMF_3 are 20 and 2 m SMF, respectively. The components in the dashed box were added for the second set of measurements.

Fig. 2.
(Color online) Spectra recorded at the indicated output energies. See text for details.

Fig. 3.
(Color online) (a) Spectrum of Stokes pulses at maximum energy before a second Stokes pulse occurs, after filtering of the original pulse. (b) Autocorrelation of the Stokes pulse.

Fig. 4.
(Color online) Spectrum that exhibits higher-order Stokes pulses.