Subpicosecond-pulse generation through cross-phase-modulation-induced modulational instability in optical fibers

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Received April 13, 1988; accepted July 8, 1988

We report subpicosecond-pulse generation at 1.319 µm in a single-mode optical fiber by modulational instability induced through cross-phase modulation by 1.06-µm pulses propagating in the normal dispersion regime. Pulse-repetition rates approaching 300 GHz were achieved.

The process of modulational instability has been modeled in various fields of physics, including fluids and plasmas. However, in the one-dimensional environment of optical fibers, the process can be relatively easily observed. In modulational instability, small perturbations of the amplitude or phase from the steady state exhibit an exponential growth owing to the interplay between the nonlinearity and the group-velocity dispersion. In the case of optical fibers, the process was originally modeled by Hasegawa and Brinkman, and their theoretical predictions were verified by Tai et al. in 1986. The nonlinearity in fibers arises because of the Kerr effect, and the instability is observed only for wavelengths in the anomalous dispersion regime. The conditions are similar to those necessary for the generation and evolution of optical solitons.

The process of induced modulational instability in optical fibers has also been considered theoretically. In this case an external amplitude modulation is applied simultaneously with a cw optical signal. By varying the power and frequency of the external modulation relative to the cw signal, solitons of controllable width and repetition rate may be generated. Tai et al. have also experimentally verified the viability of this process.

Recently, considerable theoretical attention has been given to the process of cross-phase-modulation-induced modulational instability for generating subpicosecond pulses at variable repetition rates. In addition, the process could be detrimental in amplitude-modulated multichannel communication systems, giving rise to cross talk between channels. Agrawal has shown that, even in the normal dispersion regime, the possibility exists of observing modulational instability through the cross-phase modulation of two copropagating optical fields. Schadt and Jaskorzynska have theoretically shown that it is possible to generate ultrashort pulses in the anomalous dispersion regime from a weak cw signal through modulational instability induced through the cross-phase modulation from a pulsed pump signal propagating in the normal dispersion regime. Clearly the effect is enhanced when both signals, straddling the dispersion minimum, propagate with identical or nearly identical velocities.

The experimental arrangement is shown schematically in Fig. 1. The signal was derived from a cw mode-locked Nd:YAG laser operating at 1.319 µm generating 100-psec pulses at a 100-MHz repetition rate at average powers as great as 1.8 W. Although the theoretical treatment of Schadt and Jaskorzynska relates to a cw signal, in the projected regime of subpicosecond pulse generation these 100-psec pulses were essentially quasi-cw. The pump pulses were derived from a cw mode-locked 1.06-µm Nd:YAG laser, giving ~100-psec pulses at an average (peak) power of 5 W (~500 W), also with a pulse-repetition rate of 100 MHz. The fluctuation in the power of both lasers was less than 3%, and the pulse widths were continuously monitored by using the 4% reflections off beam splitters BS1 and BS2 directed onto a synchroscan streak camera, which was driven in synchronism with the modulator frequency to the lasers.

The 1.06-µm radiation was focused into and collected out of a 2-km length of single-mode fiber F1, with a minimum dispersion at 1.48 µm, using 10× microscope objectives MO1 and MO2. A maximum launched average power of 400 mW ensured that no Stokes Raman radiation was generated, as phase shifts caused by intensity fluctuations in the pulse profile owing to stimulated Raman scattering generation would affect the cross-phase-modulation process. The effects of self-phase modulation and dispersion, however, tem-

Fig. 1. Schematic of the experimental arrangement.
Fig. 2. Series of spectra measured at the fiber output from an average signal power of 25 mW at 1.319 \( \mu \)m and average (peak) pump powers at 1.06 \( \mu \)m of (a) 0, (b) 20 mW (0.4 W), (c) 30 mW (0.6 W), and (d) 40 mW (0.8 W). The rapid growth of the modulation sidebands can be seen.

orally broadened the pulse to approximately 500 psec and generated a linear chirp across the pulse, of magnitude \(-0.02 \text{ nm/psec}^{11}\). After a variable time delay the chirped 1.06-\( \mu \)m pulses were directed off the dichroic beam splitter BS\(_3\) (high reflection at 1.06 \( \mu \)m, high transmission at 1.32 \( \mu \)m) in time synchronism with the transmitted 1.32-\( \mu \)m pulses. These pulses were then launched into fiber \( F_2 \) by using 20X microscope objective MO\(_3\).

Fiber \( F_3 \) was 1.5 km long, single mode at 1.06 \( \mu \)m, and had a dispersion minimum wavelength at 1.27 \( \mu \)m. The fiber dispersion at 1.06 and 1.319 \( \mu \)m was 26 psec nm\(^{-1}\) km\(^{-1}\) and \(-5 \text{ psec nm}\(^{-1}\) km\(^{-1}\), respectively, giving rise to a calculated interaction length between the 500-psec, 1.06-\( \mu \)m pulse and the 100-psec, 1.319-\( \mu \)m pulse of approximately 120 m. Hence in the 1.5-km-long fiber, even if total phase synchronism was completely lost, interaction between the pump and signal would still occur. The radiation leaving the fiber was collected and collimated with a 20X microscope objective and directed into a 1-m spectrograph and a scanning background-free second-harmonic-generation autocorrelator to provide simultaneous spectral and temporal resolution of 0.1 nm and 30 fsec, respectively.

The average power levels of the 1.06-\( \mu \)m radiation in the second fiber were restricted to less than 50 mW such that any stimulated Raman scattering was prevented, and these 10-nm-bandwidth pulses broadened to \(\sim\)800 psec on propagation. The average power of the 1.319-\( \mu \)m radiation was limited to 20–25 mW, which was below the threshold for modulational instability\(^4,12\) in the fiber. At these power levels only self-phase-modulation spectral broadening was observed, with no discernable pulse temporal broadening or structure.

Figure 2 shows the spectra recorded near 1.319 \( \mu \)m as a function of power at 1.06 \( \mu \)m for both laser pulses simultaneously incident in the fiber. The case for no pump present is shown in Fig. 2(a), for which the average power in the 1.319-\( \mu \)m signal was 25 mW (approximately 2.5 W peak) and the spectra exhibited self-phase-modulation broadening only to a spectral width of 1 nm. With the simultaneous introduction of 20 mW (~0.4 W peak power) of the 1.06-\( \mu \)m chirped radiation, there was a rapid growth of two sidebands symmetrically separated from the central peak by \(\sim\)8.7 cm\(^{-1}\) (260 GHz) [see Fig. 2(b)].

With a further increase in the 1.06-\( \mu \)m average pump power to 30 and 40 mW [see Figs. 2(c) and 2(d), respectively], the intensity of the sidebands grew. These sidebands in turn generated secondary bands at \(\sim\)17.8 cm\(^{-1}\) shift from the central peak. As can be seen from Figs. 2(c) and 2(d) for a 30% increase in the pump power, there was a five times increase in the intensity of the secondary peaks, which indicates the rapid exponential gain of the process predicted by

Fig. 3. Spectra recorded for an average signal power of 20 mW at 1.319 \( \mu \)m and simultaneous average pump powers of (a) 0 and (b) 30 mW at 1.06 \( \mu \)m in fiber \( F_2 \) (see text).
Typical autocorrelation trace corresponding to the power levels in Fig. 3(b). The modulational instability through cross-phase modulation is apparent, leading to 520-fsec pulses separated by 3.5 psec on top of a 100-psec pedestal. The zero intensity level is shown.

Hasegawa and Brinkman. A steadily increasing separation of the sidebands from the central frequency was also observed; this is consistent with theory. In addition, as the coefficient of cross-phase modulation is twice that of self-phase modulation, broadening of the central spectral feature near 1.319 μm would be expected. This broadening was 1.0 nm for no 1.06-μm pump power present and slowly increased to 1.35 nm for a 40-mW average pump power at 1.06 μm [see Figs. 2(a) and 2(d), respectively].

Figure 3 shows the spectra recorded under similar conditions except that the 1.319-μm signal average power was 20 mW, giving rise to a reduced self-phase-modulation-broadened profile of ~0.7 nm [see Fig. 3(a)]. When an average 1.06-μm pump power of 30 mW was introduced, cross-phase modulation contributed to a broadening of the central spectral feature to 0.8 nm, and modulational instability sidebands appeared at a separation of approximately 9.7 cm⁻¹ (~290 GHz) [see Fig 3(b)].

The corresponding time-resolved measurements showed that for 20-mW average power at 1.319 μm no temporal structure was present on the broad 100-psec pulses. In the presence of the 1.06-μm pump pulses, a distinct deeply modulated, subpicosecond-pulse structure appeared on the autocorrelation traces (see Fig. 4). The duration of the individual structured pulses was measured (assuming sech² profiles) to be 520 fsec with a temporal period between pulses of 3.5 psec, which agreed quite well with the inverse of the 290-GHz measured frequency separation of the modulational period on the corresponding spectra [see Fig. 3(b)].

Schadt and Jaskorzynska have shown that for fixed power, once a pulse has compressed in the optimal fiber distance, continuing propagation leads not to further compression of the pulses but in fact to the growth of additional sideband pulses with energy lost from the central pulse. This process was not examined experimentally, but, for a fixed fiber length, decreasing the launched signal or pump power led to a reduction of the time structure on the recorded autocorrelation traces and increased the temporal separation. This behavior is essentially the same as that predicted by Schadt and Jaskorzynska. As can be seen from Fig. 4, the femtosecond structure was on top of a long 100-psec background. A modulation depth of 60% at maximum was achieved on the autocorrelations, indicating that the pulse structure was well below the 100% modulation achievable theoretically. However, this is most likely due to the phase mismatch between the signal and pump beams, and through proper wavelength selection much higher or complete modulation should be possible. This is at present being actively investigated.

The financial support for this research by British Telecom Research Laboratories and the Science and Engineering Research Council is gratefully acknowledged.

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