Raman amplification of modulational instability and solitary-wave formation

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The effect of synchronous Raman gain in a single-mode fiber on a weak signal exhibiting modulational instability is shown spectrally and temporally to give rise to the rapid development of a single ultrashort solitary wave and a low-level dispersive pedestal.

Because of the combined effects of anomalous dispersion and the nonlinear optical Kerr effect, Hasegawa and Brinkman1 predicted that amplitude modulation or its resultant phase modulation on a cw wave in an optical fiber exhibits an exponential growth rate with the formation of solitary waves. Associated with the amplitude modulation is a characteristic modulation of the output spectra, with the frequency separation of the generated sidebands from the pump frequency being proportional to the pump-pulse amplitude.2 In addition to self-seeded modulational instability, it was shown experimentally by Tai et al.3 that a weak signal applied in synchronism with the carrier signal can induce modulational instability on the carrier at a frequency determined by the frequency difference of the signal and the carrier. Such a scheme allowed the generation of subpicosecond pulses at repetition rates greater than 0.3 THz.

In general, the frequency of the modulational instability is of the order of $10^{11}$ to $10^{12}$ Hz. As a consequence, pulsed excitation can be used to induce the instability, provided that the pump pulses have durations in the region of 100 psec or greater, such that on the time scale of the modulational instability they are effectively cw. One problem associated with the propagation of relatively long and powerful pulses over moderate lengths of single-mode fiber is that stimulated Raman scattering can give rise to the highly efficient generation of new wavelengths with an associated depletion of the pump. For silica-based fibers the peak of the Raman gain is for shifts near 400 cm$^{-1}$.4 However, significant gain can be achieved even for shifts in the region of 50–100 cm$^{-1}$. These latter shifts are typical of those generated by modest pump powers in easily available fiber lengths,3,5 and as such modulational instability can act as a preferential seed for Raman amplification with associated ultrashort pulse generation.6

In this Letter we report on the temporal and spectral development of a signal exhibiting modulational instability receiving synchronous amplification through stimulated Raman scattering in a single-mode optical fiber.

A schematic of the experimental arrangement is shown in Fig. 1. The source of pump radiation was an actively mode-locked cw Nd:YAG laser operating at 1.32 μm. This laser, which has been described in detail in a previous publication,7 generated 100-psec pulses at a 100-MHz repetition rate with an average power of 2 W, corresponding to a peak power of approximately 200 W. By using beam splitter BS$_1$, the output of the laser was divided into two equally intense beams. The transmitted beam was focused using a standard 20X microscope objective MO$_1$ into fiber F$_1$, and the radiation was collected at the fiber output using a similar objective MO$_2$.

The fiber F$_1$ was single mode at 1.32 μm and 500 m in length with a zero-dispersion wavelength in the region of 1.31 μm. At an average power of 60 mW in the fiber, the distinctive temporal and spectral features of modulational instability were observable, monitored at the fiber output. Figure 2 shows a typical spectrum recorded at this power level. The sidebands generated were ~67 cm$^{-1}$ from the central pump frequency. The inset in Fig. 2 is the corresponding autocorrelation trace, exhibiting at maximum a 50% modulation of the autocorrelation signal. The time interval between the oscillation peaks was measured to be 450 ps.

Fig. 1. Schematic of the experimental arrangement. BS$_1$–BS$_3$, beam splitters; MO$_1$–MO$_4$, microscope objectives; M’s, mirrors.
Fig. 2. Power spectrum measured at the output of fiber F1, at an average fundamental pump power of 60 mW in the fiber, clearly exhibiting modulational instability. The inset shows the corresponding autocorrelation trace.

Fsec, which corresponds reasonably well with the 497 fsec inferred from the directly measured frequency shift. This measured modulation period decreased with increased pump power and also with decreased group-delay dispersion of the fiber.²

The signal exhibiting modulational instability was then relaunched into fiber F2, where the effects of synchronous Raman amplification were examined both spectrally and temporally. The pump signal was provided by the reflected signal off beam splitter BS, and it was suitably delayed through an optical delay line such that the pump beam at 1.32 µm and the modulational instability signal entering fiber F2 were temporally coincident so as to achieve optimum Raman gain. The time synchronism was achieved by observing the relevant signals on a synchroscan streak camera driven by the modulator of the mode-locked laser.

The fiber F2 was 560 m long, with characteristics identical to those of fiber F1. As a consequence of the coupling loss in going from fiber F1 to F2 and the relaunch into a fiber with identical parameters, the spectral separation of the generated sidebands decreased and the temporal modulation period increased to more than 800 fsec for the signal level of 15-mW average power that was maintained in fiber F2.

A variable neutral-density filter in the time-delay arm permitted the pump launched into the fiber to be varied conveniently, and the effect of synchronous Raman gain on the signal was recorded. Figure 3 shows the spectral development as the pump power was varied for the fixed signal level of 15-mW average power that was maintained in fiber F2.

As the pump power increased, the spectral separation of the Stokes-generated sideband from the pump line increased to 8.2 nm (47 cm⁻¹), 8.8 nm (50 cm⁻¹), and 10.1 nm (58 cm⁻¹) for average pump powers of 10, 15, and 20 mW, respectively. Correspondingly the measured temporal modulation decreased from 680 fsec to 600 fsec to 565 fsec. At 25-mW average pump power the peak wavelength of the generated Stokes band remained relatively stationary. With a further

Fig. 3. Variation of the output spectrum from fiber F2 with synchronous pump power for a fixed average power of 15 mW in the input modulational-instability signal.

Fig. 4. Autocorrelation traces of the signal from fiber F2 for an average signal power of 15 mW and an average pump power of: a, 5 mW; b, 10 mW; c, 15 mW; d, 20 mW; e, 25 mW; f, 30 mW; g, 35 mW; and h, 40 mW.

For a 5-mW pump power, the spectrum of the emerging radiation showed a distinct broadening in the Stokes component of the modulational instability. The separation of the sidebands from the central peak was ~7.6 nm (43 cm⁻¹), corresponding to a temporal modulation of 768 fsec, which is in good agreement with the measured value of 750 fsec (Fig. 4a).
increase in the pump power, the bandwidth of the 
Stokes component broadened considerably, increasing 
from 10.7 nm at a pump power of 25 mW to ≈19 nm for 
40-mW pump power. At the latter level, the Stokes 
bond extended to beyond 1.36 μm, with the spectral 
extent increasing asymmetrically to the long-wave-
length side with pump power.
The marked change in the modulational instability 
spectra through Raman amplification was also reflect-
ed in the corresponding temporal autocorrelations. 
At low pump power (Fig. 4) the autocorrelations con-
sisted of a 30–50% modulated signal on a broad (~100-
psec) pedestal. With increased pump power the peri-
od of the temporal modulation decreased (Figs. 4a–
4c). Above 20-mW average pump power, the central 
peak of the autocorrelation began to dominate, and 
the temporal modulation period remained relatively 
constant near 565 fsec. On increasing the pump pow-
er further, the pedestal component of the autocor-
relation was reduced further and the temporal modulation 
intensity was reduced (Figs. 4e–4g).

For a pump power of 40 mW the pedestal accounted 
for only 2% of the autocorrelation intensity. A single 
Solitary wave evolved with a measured duration of 140 
fsec. If we assume hyperbolic secant pulse profiles, 
the 19-nm bandwidth of the Stokes spectrum was sup-
portive of 97-fsec pulses, and approximately 25% of 
the average power was in the solitary wave.
The difference in output due to seeding a signal can 
be seen from the result in which the total average 
power in fiber F2 was 55 mW, made up of 40-mW 
pump power and 15-mW signal power. A single pulse 
of the form shown in Fig. 4h was generated (low pedes-
tal, 140-fsec duration), and the corresponding spec-
trum is shown in Fig. 3. This should be compared 
with Fig. 2, which relates to 60 mW of pump power in 
an almost identical length of similar fiber where only 
weak modulational instability was generated. The 
Raman gain provided can be seen to have made a 
significant difference to the pulse-formation mecha-
nism.

In conclusion we have shown the significant role 
played by synchronous stimulated Raman gain on a 
low-level modulational instability signal (~15 mW) 
fed into a relatively short (560-m) length of single-
mode fiber. For relatively low pump powers (~40 
mW) a single solitary wave evolves with a dispersive 
pedestal that accounts for only 2% of the autocorrela-
tion intensity. The role played by the Raman gain 
was apparent through the changes taking place in the 
Stokes component of the modulational instability. It 
should be possible to use the high Raman gain experi-
enced by a weak seed pulse on a modulational instabil-
ity signal in a Mach–Zehnder-based interferometer to 
form the basis of an ultrafast switch.

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