INTRODUCTION

The enhancement of many nonlinear-optical processes in optical fibers, which has developed over the past 10 years, provides a convenient means of generating new wavelength ranges and of manipulating pulse shapes. However, in some cases, the low thresholds for the nonlinearities can cause problems through the generation of unwanted radiation and can set limits for useful power levels in transmission. For pulses in the picosecond–femtosecond range, self-phase modulation and stimulated Raman scattering have received particular attention, with specific reference to pulse-compression schemes in which the associated group-velocity dispersion of the ultrashort pulses plays an important role.

The effect of self-phase modulation (SPM) in fibers has been examined in detail by Stolen and Lin. The intensity-dependent nonlinear refractive index gives rise to an intensity-dependent phase shift, with an associated instantaneous frequency shift that is proportional to the time derivative of the intensity. Hence the spectrally broadened pulses exhibit a chirp, i.e., a time-dependent frequency. This mechanism forms the basis of the fiber–grating-pair pulse compressor, in which the chirped pulses are subsequently passed through a grating pair that can exhibit dispersion of the sign opposite that of the fiber, and permits temporal compression. Group-velocity dispersion (GVD) can contribute significantly to the process, in that it tends to linearize the chirp across the pulse.

An alternative means of generating short pulses is to apply a spectral windowing technique to the self-phase-modulated pulses. We showed previously, using this technique, that narrowing by a factor of ~3 can be achieved when the bandwidth of the spectral window is narrower than the SPM pulse bandwidth (by a factor of >3), provided that all other nonlinear effects can be neglected. Furthermore, the spectral window technique has been used, in conjunction with a streak camera, to provide a direct method of measurement of the degree of chirp present in a pulse. The same technique has been employed in this reported investigation, as we describe below.

Stimulated Raman scattering (SRS) in glass waveguides was first observed in 1972 by Stolen et al., and the implications of optical communications were soon realized. A pump pulse propagating in an optical fiber first creates a Stokes pulse by spontaneous Raman scattering, which is then amplified by the corresponding stimulated process. The critical power levels at which SRS becomes a dominant process in the fiber have been defined by Smith.

SRS in fibers has been used as a means of generating new wavelengths and also has served as the basis for a universal fiber-optic measurement system. More recently, we showed that the cascaded process of SRS in fibers leads to pump-pulse fragmentation and that, in the positive GVD regime, the fragments have a negative chirp that can be further compressed in a positively dispersive delay line. By using this technique, pulses of ~5 psec separated by 300 psec were derived from 100-psec pump pulses at 1.06 μm. On the other hand, SRS has been shown to introduce cross talk in multiplexed fiber systems and also should be avoided in fiber-grating compressor systems. SRS has also been suggested as a means of amplifying solitons in all-fiber communication systems, while soliton-Raman generation has been shown to be a powerful technique in the generation of frequency-tunable, femtosecond, kilowatt soliton pulses in the near infrared, in both single-pass and fiber oscillator configurations.

The results described here are concerned with the investigation of the chirp of the fundamental (1.06-μm) and Raman (first Stokes at 1.12-μm) pulses in optical fibers in a regime where ~30% of the total power was converted into the first-Stokes component. Various fiber lengths were used, from ~60 m, where there was little walk-off between the 100-psec fundamental and first-Stokes Raman pulses, to ~240 m, where walk-off was significant. A related experimental work was recently published that described operation with the pump radiation in the visible (532 nm), where GVD is much larger. In addition, recent theoretical treatments have been published on the frequency chirp of combined SRS and SPM pulses in regimes where walk-off is important or can be neglected, and both are considered in our experimental study.
EXPERIMENT

Figure 1 shows a schematic of the experimental arrangement. A cw mode-locked Nd:YAG laser (Quantronix Model 116) operated at 1.06 μm was used as the source of fundamental pump radiation. This laser system has been described in detail elsewhere.2 A synchroscan streak camera (extended Si photocathode) was used to monitor continually (with 20-psec resolution) the laser output pulses, which were maintained at 100-psec duration by adjustment to the laser cavity length. The average power from the mode-locked laser was ~7 W, corresponding to a peak power of ~700 W at the 100-MHz pulse-repetition rate.

Single-mode fiber with a cutoff at 1 μm was used; the fiber was also non-polarization-preserving with a 7-μm core diameter, 1 dB/km loss, and 35-psec/nm km GVD at 1.06 μm. Various lengths of fiber were examined: 60, 90, 120, and 240 m.

A 1-m monochromator with an 1800-line/mm grating imposed the spectral window with a minimum bandpass of 0.1 nm, and the throughput radiation was monitored on the synchroscan streak camera.

By using uncoated 20X microscope objectives a typical overall fiber-lens system, throughput efficiency of 50% was possible.

RESULTS AND DISCUSSION

As is known from previous work,19,24 the time delay between the Stokes and pump pulses is given by

\[ \Delta t = \frac{\Delta L D(\lambda) \Delta \nu}{c \nu} \]  

where \( D(\lambda) \) is the dispersion in dimensionless units \( [D(\lambda) = cD_\lambda, \text{where } D \text{ is the dispersion in picoseconds per nanometer kilometer}] \), \( \Delta \nu \) is the frequency separation between Stokes and pump, \( \nu \) is the pump frequency, and \( \Delta L \) is the fiber length. For our case \( \lambda = 1064 \mu m, \nu = 9398 \text{ cm}^{-1}, \Delta \nu = 440 \text{ cm}^{-1}, D(\lambda) = 0.011, \) and the walk-off distance for a 100-psec pulse is ~60 m. The critical power for cw SRS generation defined by Smith2 at which 50% of the pump radiation is converted to Raman signal is given by

\[ P_{cr} = kA/GL_{eff} \]  

where \( A \) is the core area of the fiber, \( L_{eff} \) is the effective interaction length, and \( G \) is the peak Raman gain, \( 9.2 \times 10^{-12} \text{ cm W}^{-1} \) at 1.06 μm. The factor \( k \) takes into account that the polarization is not maintained over the fiber length; hence the gain \( G \) is replaced by the average value \( G/2 \), and \( k \) can depend on several fiber parameters, including length, and overall can lie between 16 and 20. For our fiber parameters, \( k \approx 20 \). Stolen and Johnson19 have shown that the theoretical prediction for the critical power for pulsed excitation, although not totally accurate, is relatively well described by the above equations, agreeing with their experimentally established results. Substitution of our experimental values into Eq. (2) predicts a critical power of ~280 W, which for 100-psec pulses corresponds in this case to an average power of ~2.8 W.
The fact that 30–40% Raman conversion was possible in the 90-, 120-, and 240-m fibers at 2-W average power would indicate that the maximum signal generated was ≥1.5 times the calculated walk-off distance, in reasonable agreement with the results of Stolen and Johnson.\textsuperscript{19}

Figures 3(a) and 3(b) show typical recorded spectra for the fundamental and first-Stokes beams. They correspond to \( L = 120 \text{ m} \) and \( P = 200 \text{ W peak} \) (thus with a conversion efficiency of \( \sim 32\% \)). The spectra for all the other fiber lengths were similar, differing only in spectral width for the different fiber length–peak powers employed, and the results are summarized in Table 1. The main spectral features in the presence of significant Raman generation, principally the severe depletion of the frequency-downshifted leading edge of the pump pulse, leading to a distinct asymmetry in the spectra, have been described by several authors.\textsuperscript{21,22,25–27}

In order to measure the chirp across the pulses (both Raman and fundamental), the spectrograph was used with a...
The pump pulse for the various fiber lengths, and this is power for all cases was fixed at 200 W. In addition, the central wavelength was defined as 1064.5 nm, and the peak shown in Fig. 5 for the 90-, 120-, and 240-m fibers. The length of the spectral window, we recorded the chirp across of the longer-wavelength component. By varying the wave-
where Raman generation is minimal) because of suppression only two main features (as distinct from three; see Fig. 4a, temporal profiles through the spectral window exhibited from SPM and cross-phase modulation, the corresponding on the long-wavelength side of the induced shift resulting pulse. It should be noted that, because of Raman depletion indicating a greater frequency chirp at the front of the pump pulse, generally were shorter, compared with those in the upshifted trailing edge indicating a greater frequency chirp at the front of the pump pulse. It should be noted that, because of Raman depletion on the long-wavelength side of the induced shift resulting from SPM and cross-phase modulation, the corresponding temporal profiles through the spectral window exhibited only two main features (as distinct from three; see Fig. 4a, where Raman generation is minimal) because of suppression of the longer-wavelength component. By varying the wave-
the experiments measured wavelength shift $\Delta \lambda$ is plotted, as distinct from the usually quoted frequency shift $\Delta f$ where chirp is defined, although $\Delta f$ is proportional to $\Delta \lambda$.

For the 60-m fiber (the results are not shown in Fig. 5, for clarity) the recorded chirp was effectively linear, $\sim 0.02$ nm/psec, and did not vary when the pump power was increased to 230 W peak. Correspondingly, the chirp in the 90- and 120-m fibers, assuming linearity, was 0.014 and 0.026 nm/psec, respectively. As can be seen, the chirp in the 240-nm-long fiber was distinctly nonlinear. In addition, it was found that the chirp associated with the frequency-downshifted front edge of the fundamental pulse exhibited a measurably larger chirp, 0.029 and 0.048 nm/psec for the 90- and 120-m fibers, respectively. It is most likely that, since quite efficient Raman generation significantly modifies the frequency-downshifted rising edge of the pump pulse, reshaping and cross-phase modulation will contribute to the increased chirp on the pulse’s rising edge.

For the 240-m fiber, the discontinuity in the frequency-
downshifted region could not be fully resolved; however, such an intense feature has been predicted theoretically\(^\text{22,25}\) for the pump radiation in the regime of pulse walk-off and strong SRS generation.

A similar technique was applied to measure the associated Raman chirp, which is displayed in Fig. 6. The peak pump power was 200 W with the exception of the result for 60 m, where 230 W was used. Several interesting features appear that should be noted. Primarily, the chirp for the Raman signal is significantly larger than that of the corresponding fundamental pulse, 0.53, 0.21, 0.15, and $\sim 0.09$ nm/psec (in the initial approximately linear region) for the 60-, 90-, 120-, and 240-m lengths, respectively. Consequently the chirp of the Raman component in the 60-m fiber was approximately 25 times that of the fundamental, with this ratio decreasing

![Fig. 5. Measured chirp of 1.06-μm pump pulses for the different fiber lengths employed. The peak power was 200 W, and the central wavelength was defined to be 1064.5 nm.](image)

bandpass of 0.2 nm (for the measurements near 1.12 μm).

The basis for the spectral window mechanism is explained in Ref. 6. For a pulse that suffers only the action of SPM (narrowing also occurs in the presence of SPM and GVD effects), a pulse narrower than the input by a factor of $\sim 2.5 \times$ is expected after the spectral window. In Fig. 4a this is shown to be the case for a fiber length of 240 m with a peak power of $\sim 100$ W for an input pulse width of 100 psec, where a 40-psec pulse was recorded after the spectral window.

In the spectral windowing technique, maintaining a fixed bandpass and scanning across the spectrally broadened pulse profile should keep the temporal width of the transmitted signal constant, allowing it to move only in time according to the degree of chirp across the input pulse. This, however, is true only provided that no other nonlinear mechanism is present, i.e., the chirp is assumed to be linear across the pulse.

At a peak power of 200 W in the 240-m fiber with 37% Raman conversion, the effect of additional nonlinearity through the Raman process can be seen through the spectral window mechanism; see Fig. 4b. The pulses were recorded at central wavelengths of 1, 1063.5 nm; 2, 1064.0 nm; and 3, 1064.5 nm. Clear variations of the recorded pulse widths indicate a nonlinear chirp. Beyond the region shown in Fig. 4b, the streak-camera-recorded temporal pulse profiles in the frequency-downshifted leading edge of the pump pulse, where Raman depletion is most severe, generally were shorter, compared with those in the upshifted trailing edge indicating a greater frequency chirp at the front of the pump pulse.

In addition, by varying the wave-length of the spectral window, we recorded the chirp across the pump pulse for the various fiber lengths, and this is shown in Fig. 5 for the 90-, 120-, and 240-m fibers. The central wavelength was defined as 1064.5 nm, and the peak power for all cases was fixed at 200 W. In addition, the
Fig. 7. Effect of spectral window on the Raman pulses, as recorded using a streak camera, showing the strong nonlinearity of the chirp across the pulse. The fiber length was 240 m, the peak power was 200 W, and the central wavelengths were

- a, 1111 nm
- b, 1120 nm
- c, 1131 nm

with length to ~7 and ~3 times for the 90- and 120-m fibers. Significantly greater chirp in the Raman component was observed in the visible by Stolen,\textsuperscript{19} and an increase has been theoretically predicted by Lugovoi.\textsuperscript{28} Therefore it can be seen that, in the absence of dominant GVD effects, for the case of the 60-m fiber, which is approximately the walk-off distance, the Raman pulse is generated with a chirp many times that of the fundamental pump-pulse chirp, which decreases through propagation.

This behavior can most likely be explained simply in terms of GVD. From Table 1 it can be seen that the width of the Raman spectra has practically been established at 90 m and that little further broadening takes place and SPM broadening is not so dominant. Assuming a GVD of \( \sim 30 \) psec/nm km for a \( \sim 100\)-psec Raman pulse for the 240-m fiber gives an approximate broadening to \( \sim 245 \) psec for the 20-nm spectrally wide pulse. Hence, assuming a totally linear chirp over the full pulse width, an approximate chirp of \( \sim 0.08 \) nm/psec is calculated. Similarly, values for the 120- and 90-m fibers are 0.11 and 0.12 nm/psec, respectively, in fair agreement with the experimental values of 0.09, 0.15, and 0.21 nm/psec for the 240-, 120-, and 90-m fibers.

Fig. 8. Streak-camera records of the effect of the GVD on the arrival time of Raman pulses (right-hand side) with respect to the pump pulse (center) for different fiber lengths: a, 60 m; b, 90 m; c, 120 m; and d, 240 m.
It should be noted that the Raman chirp in the 60-m fiber was measured only over the central 30 psec of the pulse. Theoretical treatments have shown that high gradient chirp features are present in this regime,\textsuperscript{21,22,25} which will decrease and linearize owing to GVD.

A measurably higher chirp was present on the frequency-downshifted leading edge of the Raman pulses, and in our region of detection this was linear for the 60- and 90-m fibers. For the 120- and 240-m fibers deviation from linearity was clearly apparent, and this was associated with the detection of the cascade generation of the second-Stokes component at \( \sim 1.18 \) \( \mu \)m, which tends to deplete the leading edge of the first-Stokes pump pulse.

The highly nonlinear nature of the first-Stokes Raman chirp in the presence of GVD effects for the 240-m fiber is apparent from the synchroscan streak-camera records shown in Fig. 7, recorded at a peak pump power of 200 W. For a perfectly linear chirp, the spectral window technique should generate pulses of equal duration at different wavelengths. The measured pulse widths of \( (\text{Fig. 7a}) \) 101 psec, \( (\text{Fig. 7b}) \) 64 psec, and \( (\text{Fig. 7c}) \) 46 psec at 1111, 1120, and 1131 nm, respectively, also indicates that the chirp was decreasing with decreased wavelength.

The spectral windowing technique was also used to measure the temporal separation of the central wavelengths of the fundamental and first-Stokes Raman pulses and, through the use of Eq. (1), to estimate the source of the Stokes pulse. This was done by a double-exposure method on the streak camera. First the monochromator was centered at 1064.0 nm and the fundamental pump pulse was stored. The monochromator was then centered at 1119 nm and the streak stored on top of the original image; hence pump and Raman beams could be temporally displayed simultaneously.

Figure 8 shows the recorded images for the fiber lengths examined. It should be noted that time increases to the left on the figure. The pulses to the extreme right are the Raman pulses, those to the center the central peak of the pump pulse, and those to the left an artifact of the spectral windowing, i.e., the trailing-edge component.\textsuperscript{42} Since all pulses recorded under different conditions, the time scan of the camera was not the same for all measurements. The calculated time delays for the fiber parameters are 103, 154, 206, and 412 psec for the 60-, 90-, 120-, and 240-m lengths, respectively, and those measured experimentally were 75, 150, 212, and 406 psec. Similar to the results of Stolen and Johnson,\textsuperscript{19} these values would indicate [if Eq. (1) were used] that the source of the Raman pulse is just inside the fiber input face, apart from the case of the 60-m fiber, where it was measured to be about 15 m inside. However, error in the determination of the central wavelength of one pulse may have led to the discrepancy between the theoretical and experimental values.

\section*{CONCLUSION}

Using the spectral windowing technique in association with a synchroscan streak camera, we have measured the associated chirp of the fundamental and Stokes pulses in various lengths of single-mode optical fiber, covering one to four walk-off distances. All pulses exhibited larger chirps on their frequency-downshifted leading edges, and deep modulation of the chirp was observed on the fundamental for the longest fiber lengths. Clear variations of the rate of change of chirp on the leading edge of the fundamental and first-Stokes pulses for the longer fiber lengths were most likely due to the generation of the first-Stokes and second-Stokes signals, respectively.

Although the Raman component exhibits a nonlinear chirp, an approximate linearity extends over significant ranges, and it may be possible through spectral selection and compensation with a conventional grating pair to achieve pulse compression of spectral regions of the Raman pulses. However, in subsequent measurements we have so far failed to achieve any significant compression.

For the shortest fiber length, for which dispersion was less significant, the Raman pulse was generated with a chirp many times that of the fundamental pulse, which recent theoretical considerations\textsuperscript{22,25} have shown to be associated with pump depletion and GVD.

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\section*{REFERENCES}


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