Figure-of-eight fiber lasers (F8Ls) employ passive interferometric mode locking in a nonlinear amplifying loop mirror (NALM) and feedback to generate short optical pulses. Various rare-earth-doped fibers, such as erbium, ytterbium, ytterbium–erbium, and praseodymium, have been used as the gain medium in such configurations to achieve short pulses in the 1.55, 1.30, and 1.07-μm spectral ranges. In all these cases spectral operation of the laser is limited by the gain band of the rare-earth dopant.

Raman scattering is an alternative gain mechanism in standard optical fibers that has received attention for use in wavelength-flexible cw and pulsed lasers and amplifiers. Raman gain is not limited to any one spectral region and, with a suitable pump source, can be used in standard single-mode fibers across the 1–1.8-μm spectral region. In addition, the broad Raman gain bandwidth in fibers can support subpicosecond pulse durations.

In this paper the spectral limitations of rare-earth-dopant gain are overcome by the use of fiber Raman gain in several compact F8L configurations, yielding subpicosecond pulses. Systems at 1.57, 1.33, and 1.41 μm are described, although operation in other wavelength ranges is possible with a suitable pump source, fiber, and components. Note that Raman gain was used in a NALM before but for soliton switching and with a pulsed pump source.

Figure 1 shows the experimental configuration of the 1.57 μm Raman F8L. The NALM and feedback loops are depicted at the right and the left, respectively, joined by a fiber coupler that was 50:50 transmissive at 1.56 μm. Raman gain in the NALM took place in 2.1 km of dispersion-shifted fiber (DSF) with zero dispersion at 1537 nm. The Raman pump source consisted of a cw 1455 nm fiber Raman laser that was coupled to and removed from the NALM by use of two couplers. Up to 3.1 W of pump power was launched into the DSF. The Raman signal was extracted from the F8L after the NALM through a 20% output coupler in the feedback ring. The remaining 80% of the signal was passed through a 3 nm bandwidth tunable-bandpass filter (TBPF) and a 1.55 μm isolator before being relaunched into the NALM. The isolator ensured unidirectional operation in the feedback loop. Polarization controllers were used in the two loops to optimize the NALM switching process. In the NALM, the couplers used to launch and extract the pump also served to maintain the signal within the ring. Note that the 50:50 coupler transmission profile was chosen to direct any remaining 1455 nm pump against the isolator. The Raman output signal was observed by use of an optical spectrum analyzer, a background-free noncollinear autocorrelator, and an analog oscilloscope.

The 1.33 and 1.41 μm Raman F8Ls had the same ordering of components as the 1.57 μm F8L. Differences in the 1.33 μm F8L were that it had a 1257 nm fiber Raman laser with up to 5.2 W of power, the Raman gain fiber was a 2.0 km standard telecommunications fiber, the TBPF had a 0.9 nm bandwidth, the isolator was optimized for transmission at 1.3 μm, the loop-joining fiber coupler was 50:50 at 1.33 μm, and the output coupler extracted only 10% of the Raman signal. In the 1.41 μm Raman F8L a TBPF was not available. The pump in this case was a 1316 nm fiber Raman laser with up to 5 W of power, the gain medium was a 4.5 km standard telecommunications fiber, the loop-joining coupler was 75:25 at 1.41 μm, the isolator was optimized for 1.3 μm, and the output coupler extracted 20% of the signal.

Typical Raman gain bandwidths in each fiber were measured to be approximately 50–60 nm. The gain spectra had the characteristic double-peaked profile with peak gain at 1555, 1333, and 1398 nm in the 1.55 μm Raman F8L.
three cases. In single pass with pump powers of the order of that used in the F8Ls, the Raman-amplified spontaneous emission narrowed to a 10–20 nm bandwidth. In the F8Ls the gain bandwidths were also restricted by the couplers, isolators, and TBPFs.

Figure 2 shows the signal output of the 1.57 μm F8L for 2.2 W pump power. The spectrum in Fig. 2(a) depicts a main peak at 1564 nm and a broad, ~10 dB lower background that extends toward 1.6 μm. The main peak corresponds to the TBPF setting, and the broad background corresponds to solitons that have redshifted by the soliton self-frequency shift (SSFS).9

Figure 2(b) (solid curve) shows the associated autocorrelation of the 1.57 μm F8L output. The peak corresponds to fundamental solitons of 440 fs duration that exist in the redshifted part of the signal spectrum in Fig. 2(a). The autocorrelation exhibits an ~12% background that is due to dispersive waves caused by nonadiabatic soliton formation. In addition, during initial pulse development from Raman noise, the lower soliton power that corresponds to these broader pulses leads to multiple fundamental solitons randomly forming and self-frequency shifting at a given power. The resultant random sequence of solitons also contributes to an autocorrelation pedestal.

The output average signal power was 23.3 mW for 2.2 W pump power and, from spectral analysis, ~6% of that power, or ~1 mW, propagates as solitons. Increases in pump power caused the solitons to shift toward 1.58 μm through the SSFS and the autocorrelation background to increase to ~20% of the peak (for 2.8 W pump power). This increased background is a result of a larger number of solitons that are irregularly sequenced because of fiber dispersion differences across the broadband Raman signal.

The 1.57 μm F8L output was passed through an erbium-doped fiber amplifier (EDFA) and a nonlinear optical loop mirror (NOLM) to separate the solitons from the dispersive wave background.10 The NOLM consisted of 400 m of DSF with zero dispersion at 1544 nm, closed by a coupler that was 50:50 transmissive at 1.56 μm. Polarization controllers were included inside and outside the NOLM to optimize soliton switching. The length of the DSF corresponded to approximately eight soliton periods for solitons of 440 fs duration. The dashed curve in Fig. 2(b) displays the resultant autocorrelation with a lower background of ~7% that is due primarily to the irregular soliton sequence. Various fiber delay lines were used to verify that the F8L output was indeed pulses and not noise bursts or cw. The pulse train was also observed, with a photodiode on an analog oscilloscope, to exhibit a random repetition frequency but stable behavior.

Various filters with bandwidths from 0.9 to 12.8 nm were used to optimize the 1.57 μm system. In all cases, including not using a TBPF, similar soliton durations of ~440 fs were obtained. The effect of the TBPF was to vary the autocorrelation background. With the 12.8 nm or no TBPF, a broad spectral peak with 5–6 nm linewidth and an autocorrelation with ~30% background were obtained. This high background is due to the larger range of soliton wavelengths and the irregular pulse sequence that result from fiber dispersion differences. Filters with narrower bandwidths limited the signal linewidth, the number of solitons at different wavelengths, and, hence, the autocorrelation background. Using an excessively narrow TBPF, such as the 0.9 nm filter, however, generated an additional, broader background autocorrelation pulse. In these cases the filter clips the soliton spectrum and results in longer pulses with larger soliton periods entering the NALM.11 Raman gain in the NALM causes soliton compression. However, if excessive amplification takes place across each soliton period, nonadiabatic soliton compression will occur, causing the formation of dispersive waves. The relatively low dispersion of the cavity can cause these waves to appear as background pulses in autocorrelations.

With the 0.9 nm TBPF, ~7 ps pulses were formed by spectral clipping that correspond to an ~7 km soliton period in the DSF. All the Raman amplification then took place within a single soliton period, causing nonadiabatic compression and the generation of dispersive waves. With the 3 nm TBPF, the signal linewidth entering the NALM was ~2 nm, which corresponds to a Fourier-transform-limited soliton duration of ~1.3 ps and a soliton period of ~300 m in the DSF. In this case temporal compression to ~400 fs was more adiabatic, as there was less...
amplification per soliton period and less energy propagated in dispersive waves. The 3 nm TBPF position in the cavity was changed to the NALM output directly before the output coupler to confirm this. The resultant output lacked the SSFS background spectrum, and temporally a longer pulse with a 1.46 ps duration was obtained. This result confirmed that the solitons reacted to gain and loss around the cavity and that compression to subpicosecond durations took place each round trip in the NALM. Note that, with the filter in its original position, tuning did not change the soliton wavelength. Spectrally the TBPF peak and dispersive waves could be translated over ~20 nm, but the solitons always shifted in the NALM via the SSFS toward the Raman gain peak.

Figure 3(a) shows the spectral and temporal results for the 1.33 μm Raman F8L. A spectrum similar to that of the 1.57 μm F8L, was obtained with a 1329 nm main peak corresponding to the TBPF wavelength and a redshifted background corresponding to SSFS solitons. Temporally, as shown in the inset, the autocorrelation had an ~10% background and a peak corresponding to 500 fs solitons. As was found with the 1.57 μm F8L with a 0.9-nm TBPF, the narrow bandwidth of the filter resulted in soliton spectral clipping and generation of dispersive waves in the NALM. These ~10 ps dispersive waves were observed in this case with a lower autocorrelation resolution. From spectral analysis, for 5.2 W pump power, ~10 mW of the average output power was present in the solitons.

Figure 3(b) depicts the 1.41 μm Raman F8L results for 5 W pump power. A broad 2.8 nm signal linewidth was obtained in this case, as an appropriate TBPF was not readily available for this wavelength range. Similar broadband spectra were obtained in the 1.33 and 1.57 μm cases when the TBPFs were removed. Temporally, as was observed in the 1.57 and 1.33 μm F8Ls without a TBPF, a high ~30% autocorrelation background was obtained owing to fiber dispersion differences across the broad signal bandwidth. The autocorrelation peak corresponded to a soliton of 860 fs duration. The use of better-optimized components is expected to result in shorter pulses in this case.

In the three F8L cavities the Raman gain fiber dispersion, effective area, length, and nonlinearity were chosen to maximize Raman scattering while minimizing the soliton threshold power and soliton period. As the 1.33 and 1.57 μm systems had similar fiber lengths and operated near zero dispersion, they had similar outputs. The 1.41 μm system, however, operated with higher dispersion in a longer fiber and, hence, produced longer pulses. This system could be optimized by use of a shorter fiber length with zero dispersion near 1.4 μm.

In conclusion, the wavelength flexibility of fiber Raman gain was used in several F8L configurations to produce subpicosecond soliton trains. Other wavelength ranges could easily be accessed with an appropriate Raman pump source, gain fiber, and components. An interactivity modulator or other timing regularization techniques could be incorporated into the configurations for applications that require pulse train regularity. These sources have the potential of being compact and robust and could be used in wavelength ranges not covered by rare-earth-doped fiber or other standard laser systems.

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References