Cascade Raman soliton fiber ring laser

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Received June 8, 1987; accepted August 5, 1987

Pulses as short as 200 fsec at 1.5 pm and 230 fsec at 1.6 pm have been generated through a cascade Raman, solitonlike process in a fiber ring oscillator. A dispersion-shifted (\( \Delta n = 1.46 \mu \text{m} \)) single-mode fiber was used as the gain medium, which was synchronously pumped by a cw mode-locked Nd:YAG laser operated at 1.32 \( \mu \text{m} \).

The exploitation of stimulated Raman scattering in optical fibers as a scheme for soliton generation was first proposed in 1983 by Vysloukh and Serkin.\(^1\) They relied on the fact that the broad Raman-gain bandwidth of silica-based fibers\(^2\) should permit the generation of pulses of the order of 100 fsec in the regime where pulse broadening due to self-phase modulation was balanced by negative group-velocity dispersion. In the positive-group-velocity dispersion regime, fiber Raman laser systems have been extensively used in various cavity configurations\(^3\) to provide widely tunable picosecond pulses. Operation with negative group-velocity dispersion has been described by Lin and Glodis\(^4\); however, the potential of stable, ultra-short soliton Raman generation was not realized, possibly because of the inclusion of intracavity, bandwidth-limiting tuning elements. However, since 1985 several experimental techniques have been described\(^5-11\) that permit femtosecond soliton-pulse generation through stimulated Raman scattering in fibers, and the potential simplicity of some of these systems\(^8,9,11\) makes them an attractive alternative to color-center lasers\(^12\) and to the soliton laser\(^13\) as a source of femtosecond pulses with kilowatt powers in the near infrared.

Reported soliton Raman fiber laser sources, with two exceptions,\(^5,6\) have operated in the spectral region between 1.37 and 1.49 \( \mu \text{m} \) and have operated on the first Stokes Raman band. In this Letter we report a synchronously pumped cascade-Raman solitonlike pulse-formation mechanism in a fiber ring geometry, with a cw mode-locked Nd:YAG laser operating at 1.32 \( \mu \text{m} \) as the pump source.

The experimental arrangement of the fiber ring-laser system is shown in Fig. 1. A cw mode-locked Nd:YAG laser (Quantronix Model 116) operating at 1.32 \( \mu \text{m} \) was used as the source of fundamental radiation. Pulses of \( \sim 100 \) psec were routinely produced at a 100-MHz repetition rate with an average power of up to 2 W (\( \sim 200 \) W peak). The pump radiation was directed off the beam splitter BS (\( \sim 100\% \) R at 1.32 \( \mu \text{m} \), <5% R above 1.4 \( \mu \text{m} \)) and, by a 20X infrared antireflection-coated microscope objective L\(_1\) into the fiber. The silica-based fiber was nonpolarization preserving, single mode at 1.32 \( \mu \text{m} \), and of a multiple-index design\(^14\) with a central graded core of 7-\( \mu \text{m} \) diameter. In the spectral region 1.2 to 1.65 \( \mu \text{m} \), the loss was less than 0.6 dB/km, with the exception that in the region of the water absorption around 1.39 \( \mu \text{m} \) the loss rose to \( \sim 2 \) dB/km. The low OH content was essential to prevent attenuation of the first Stokes band. The fiber was tailored\(^5\) to have its dispersion minimum in the region of 1.46 \( \mu \text{m} \), which ensured an efficient cascade-Raman generation and negative dispersion in the required 1.5-\( \mu \text{m} \) regime. With pumping at 1.32 \( \mu \text{m} \), the first Stokes band occurs at 1.4 \( \mu \text{m} \) in the region of positive group-velocity dispersion. For a walk-off of 100 psec between pump and Raman beams, a fiber length of \( \sim 250 \) m is required; hence efficient conversion to the first Stokes Raman band is possible, which can subsequently act as the pump source in a cascade for the generation of the second Stokes component in the negatively dispersive regime.

On leaving the fiber, where typically an overall power-coupling efficiency of \( \sim 40\% \) was achieved, the radiation was collected and collimated with an identical (L\(_2\)) microscope objective to that used at the input, and the light was directed through the aluminum-coated mirrors (M\(_1\) and M\(_2\)) through the beam splitter.
Fig. 2. Spectra recorded for a 600-m fiber length for an average pump power of 500 mW at 1.32 \( \mu \)m (a) without and (b) with feedback.

BS into the input focusing microscope objective. A 5-\( \mu \)m-thick pellicle P was included intracavity, to act as a bandwidth-limiting element and to permit tuning over the spectrally broad Raman bands. Synchronization of the fed-back Raman signal with the input pump pulses for maximum amplification was achieved by mounting the fiber-end lens \( L_2 \) assembly on a translation stage, which was driven with micrometer precision.

Two different lengths of fiber, 400 and 600 m, were used in the laser arrangement. Similar spectral and temporal behavior was obtained under both conditions; however, the threshold for laser operation, as expected, was higher for the shorter fiber length. Figure 2 shows the spectra obtained in single pass and in laser operation for the 600-m fiber length pumped at an average power of 500 mW (\( \sim 50 \)-W peak power). The spectra were recorded using a 0.25-m scanning monochromator in conjunction with a germanium photodiode and with a spectral resolution of \( \sim 4 \) nm. Figure 2(a) shows the single-pass spectrum, where only the fundamental (1.32-\( \mu \)m) and first Stokes (1.41-\( \mu \)m) Raman bands were observed. Conversion to the first Stokes Raman band was greater than 50%. The narrow line at 1.356 \( \mu \)m was attributable to a four-wave mixing process and was observed and reported previously.\(^{11}\) In laser operation, for the cavity length optimized for operation at 1.5 \( \mu \)m on the second Stokes band, the spectrum shown in Fig. 2(b) was obtained. At the high peak pump powers used, oscillation on the third Stokes band (\( \sim 1.6 \) \( \mu \)m) was also possible simultaneously with the second Stokes. When the pump powers were varied, no detectable shifts in the lasing maxima of the Stokes bands were observed.

Streak-camera measurements were taken of the temporal behavior of the fundamental and Raman bands in the single-pass and feedback conditions. The first Stokes Raman pulse, which had a duration of 50 psec in single pass, was severely depleted and fragmented in the oscillator configuration, with an effectively broader half-width of \( \sim 100 \) psec through depletion. At 1.5 \( \mu \)m the soliton Raman pulses were temporally limited by the resolution of the synchroscan streak camera to \( \leq 30 \) psec.

Higher temporal resolution of the generated soliton Raman pulses at 1.5 and 1.6 \( \mu \)m was used through a conventional noncollinear second-order autocorrelation employing a 1-\( \mu \)m-thick LiIO\(_3\) crystal, with a resolution of better than 100 fsec, to determine the pulse widths. These are shown in Figs. 3a and 3b for the second and third Stokes Raman pulses, with measured pulse widths (assuming \( \text{sech}^2 \) profiles) of 200 and 230 fsec at 1.5 and 1.6 \( \mu \)m, respectively. Later experiments have shown that, if the cavity is optimized, substantially shorter pulses (\( \leq 150 \) fsec) can be generated.

The measured bandwidths of the Raman components of \( \sim 80 \) nm under transform-limited operation could support a pulse width of \( \sim 30 \) fsec in the region of 1.5 \( \mu \)m. It is most likely that the Raman pulses exhibit a distinct nonlinear chirp, as has been described by several authors\(^{16-18}\) and has been observed in the positive-group-velocity dispersion regime.\(^{19}\) Since for some applications transform-limited operation may be preferred, a spectral filter with a reduced bandwidth but capable of supporting a 150–200-fsec pulse could be placed intracavity.

The autocorrelations revealed that the degree of the nonsoliton part of the pulse, generally visible as a long-duration pedestal, was in most cases not apparent and was less than 0.2% of the maximum autocorrelation

Fig. 3. Background-free autocorrelation traces of soliton Raman-generated pulses: a, in the second Stokes band at 1.5 \( \mu \)m and b, in the third Stokes band at 1.6 \( \mu \)m for a 600-m fiber laser pumped with 500 mW of average power at 1.32 \( \mu \)m.
generated in 150-fsec pulses (~5.6-kW peak power) at 1.32 µm, as much as 100 mW of average power can be obtained in the 1.5- and 1.6-µm regimes around 1.5 and 1.6 µm with peak powers of ~200 fs. Further results have shown that, with appropriate cavity optimization, as much as 100 mW of average power can be generated in 150-fsec pulses (~5.6-kW peak power) at 1.5 µm.

The overall financial support for this work by British Telecom is gratefully acknowledged. The research of A. S. Gouveia-Neto and A. S. L. Gomes is supported by scholarships from Coordenação de Aperfeiçoamento de Pessoal de Ensino Superior and the Conselho de Desenvolvimento Científico e Tecnológico (CNPq) Brazilian agencies. The authors thank the director of British Telecom Research Laboratories for permission to publish.

References