Broadband Continuum Generation in Single-Mode Optical Fiber

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ABSTRACT

We report broadband continuum generation in a single-mode step-index optical fiber pumped by the second harmonic (532 nm) of a Nd:YAG laser. The continuum started to appear together with the first-order Stokes at 545 nm with an input power of 11 mW. The appearance of the second-order Stokes is distinctly observed at 557.5 nm for 96 mW input power. The generated continuum spans 123.12 THz (550–712 nm). Asymmetric cross-phase modulation-induced spectral sidebands were also observed.

INTRODUCTION

Frequency conversion and broad supercontinuum generation (SCG) techniques are presently developed for a variety of applications where laser sources of several emission wavelengths play a significant role. In optical fibers, nonlinear and dispersion processes permit frequency shifting and generation of supercontinuum. The most studied nonlinear effects are stimulated Raman scattering (SRS) for multiple wavelength generation and together with dispersion, self-phase modulation (SPM), and cross-phase modulation (XPM), these processes act together to generate a continuum.

SRS in an active media has found applications such as a tunable light source for imaging, spectroscopy, and ultrashort pulse generation (Palero et al., 2002). In optical fibers, conversion of a single wavelength into several frequencies opens up new possibilities especially as highly tunable light source (Ilev et al., 1996; Gavrilovic et al., 1998) for wavelength-division-multiplexed (WDM) systems (Arya, 1997), signal amplification (Desurvire, 1994), and as a new tool for beam cleanup and combining (Russel et al., 2002). On the other hand, supercontinua find applications in optical metrology, spectroscopy, optical coherence tomography, and optical communications (Zhao et al., 2003; Mussot et al., 2003; Lu & Knox, 2004).

When a pump wave of energy greater than or equal to the threshold is coupled into an optical fiber, nonlinear effects can occur.

SRS in optical fibers results from inelastic scattering of high-energy photons by the molecules of the Raman-active media. The high-energy photons excite silica molecules from lower- to higher-energy levels which generate frequency-shifted photons during its relaxation to lower-energy states. This shift in frequency occurs in units of the vibrational frequencies of silica. The shifting to lower and higher frequencies is called Stokes and anti-Stokes shifting, respectively. Multiple Raman lines are generated by SRS cascade and four-wave Raman mixing (FWRM).

SPM and XPM are nonlinear refractions due to the intensity dependence of the refractive index. SPM refers

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to the self-induced time-dependent phase shift experienced by the field as it propagates along the fiber. Time dependence of the phase shift results in the creation of new frequencies. XPM is similar to SPM except that shifting is induced by copropagating fields of different wavelengths. XPM induces an asymmetrically broadened spectrum (Agrawal, 1995).

Broadband continuum generation can be enhanced by using highly nonlinear fibers. This can be done by increasing the optical density of the fiber, which includes a tapering method (Lu & Knox, 2004) and launching high-power lasers. Supercontinuum has already been observed in birefringent (Zhao et al., 2003), dispersion-shifted (Mussot et al., 2003), and photonic crystal fibers.

In this paper, we report the generation of broadband continuum of the 532 nm laser pulse in a 51 m step-index optical fiber. Pump power dependence of the spatial extent of the continuum is presented as well as the observed XPM-induced modulational instability of the Rayleigh scattered line.

EXPERIMENTAL SETUP

Figure 1 shows a schematic of the experimental setup employed. The excitation source is the linearly polarized second-harmonic (532 nm) output of a *Q*-switched Nd:YAG laser (Spectra Physics GCR-230) operating with a pulse width of ~7 ns and 10 Hz repetition rate. An iris (D) is introduced for spatial filtering of the laser beam. Light is collimated using two lenses, L1 and L2, of focal lengths 250 and 11 mm, respectively. The input is focused into a 51-m-long optical fiber (OF). Light is coupled onto the fiber using an aspheric lens (L3), which has a numerical aperture (NA) of 0.25 and a focal length of 8 mm.

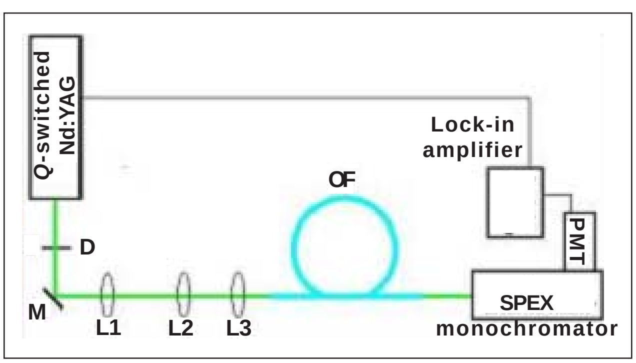

Fig. 1. Schematic diagram of the experimental setup.

The medium is a commercially available step-index single-mode optical fiber (Newport model F-SV). It is designed to operate at 633 nm with the single-mode cutoff condition at 550±50 nm. The fiber has a mode field diameter of 4.3 mm and NA of 0.14. The outer cladding diameter of 125 mm is exposed by manual stripping and cleaving. The quality of the cut end faces are examined using a microscope.

The output light of the fiber is fed directly into the monochromator (SPEX 1000M) of which the slit width is set at 200 mm. The monochromator is connected to a photomultiplier tube (PMT) (Hamamatsu R-1328U5) and the signal is digitized through a lock-in amplifier (SRS-SR830). Input power measurement was done using the Molectron detector and power meter.

RESULTS AND DISCUSSION

Figure 2 shows the initial spectral evolution of the 532 nm pump. At the lowest input power of 11 mW, the first-order Stoke (S1) was observed at 545 nm corresponding to a shift of 448.37 cm^{-1}. This line is observed to broaden from a width of 4 nm at 11 mW to 5.5 nm at 96 mW pump. A continuum starting at 550 nm spanning 11.64 THz was generated together with the first Raman line.

As the pump power is increased (Fig. 3), the continuum broadens extending up to the red region at 712 nm spanning a 123.12 THz frequency range. Table 1 summarizes the frequencies spanned by the SCG with increasing power.

Following the spectral evolution up to 96 mW input, the second-order Stokes (S2) is clearly seen at 557.5 nm with a spectral shift of 859.77 cm^{-1}. This line with a full width at half maximum (FWHM) of 5 nm has a lower intensity compared with S1 as a result of energy transfer during multiple scattering. The S1 line increases in intensity up to 50 mW and experiences a noticeable decrease at 80 mW and a considerable gain at 96 mW.

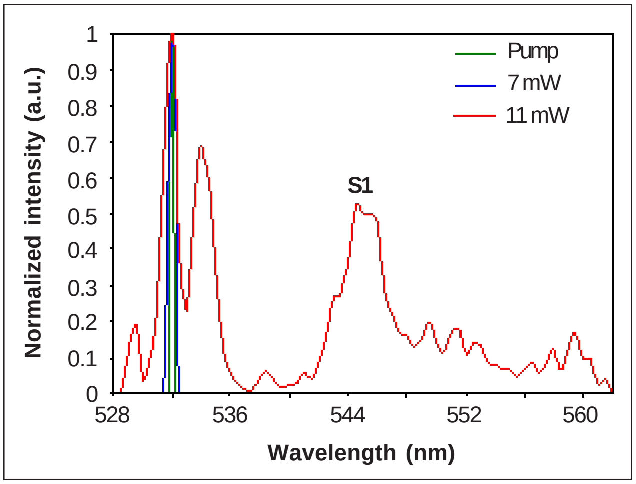

Fig. 2. Spectrum on the fiber output featuring the evolution of the 532 nm laser pulse towards the first-order Stokes S1 and generation of spectral sidebands with increasing power.

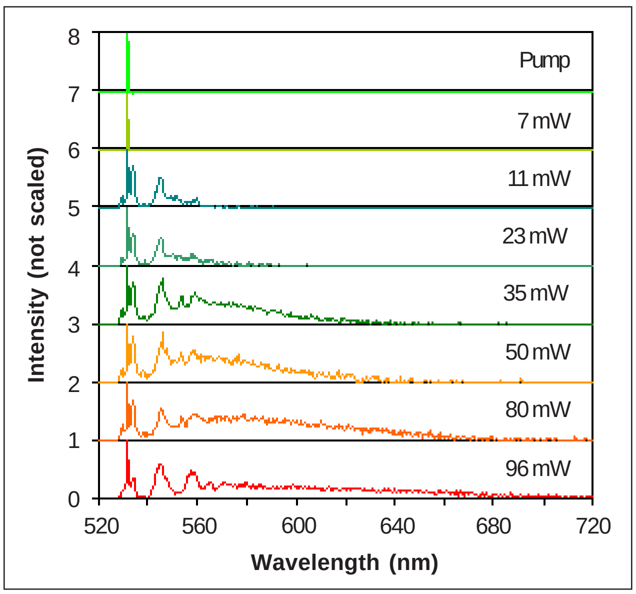

Fig. 3. Output spectra of the 51-m-long single-mode fiber for different pump powers.

Table 1. Frequency spanned by the broadband continuum generated for different input power.

Ave. pump power (mW)	Spanned frequency (THz)
7	—
11	11.64
23	17.28
35	69.26
50	80.34
80	101.01
96	123.12

A decrease in the intensity of S1 can be due to the transfer of energy to the continuum and the generation of S2. No anti-Stokes orders are generated even at this intense energy of 96 mW. The absence of blueshifted lines can be attributed to the fact that the phase-matching condition, a requirement of four-wave mixing, is difficult to satisfy in silica fibers (Agrawal, 1995).

An average decrease in the energy of the continuum was observed for the maximum input power employed probably because of the transfer of energy to longer wavelengths. A continuum was also observed by Krylov et al. (1998) after the first Stokes was generated in SRS by a femtosecond laser in hydrogen gas and has attributed the continuum to white-light generation by SPM.

Another interesting feature is the presence of spectral side lobes with a frequency separation of 4.77 THz (4.5 nm) near the Rayleigh line (Figs. 2 and 3). The presence of these sidebands results from the spectral manifestation of modulational instability induced by XPM. A thorough discussion on XPM and XPM-induced modulational instability is given by Agrawal (1987 & 1995). This observation suggests the possibility that XPM can sustain solitons in the normal dispersion regime (Agrawal, 1987). The intensities of the first (529.5 nm) and second (534 nm) sidelobes reached their maximum at 35 and 50 mw, respectively. Their energies begin to drop at 50 and 80 mW, correspondingly. No change in the relative positions of the sidelobes was observed for different pump powers.

CONCLUSION

Broadband continuum generation of a pulsed Nd:YAG laser operating at 532 nm has been observed in a 51-m-long step-index single-mode optical fiber. The continuum supports a 123.12 THz frequency range extending from 550 to 712 nm for an average pump power of 96 mW.

The first Raman line (S1) occurs at the lowest input of 11 mW with a spectral shift of 448 cm^{-1} at 545 nm. The second-order Stokes is clearly defined at the maximum pump where the longest continuum occurs. It has a shift of 859.77 cm^{-1} at 557 nm. Spectral sidelobes induced by XPM was also observed.

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