Laser Physics, Vol. 14, No. 5, 2004, pp. 748–751.

Generation of Self-Frequency-Shifted Solitons in Tapered Fibers in the Presence of Femtosecond Pumping

S. M. Kobtsev, S. V. Kukarin, N. V. Fateev, and S. V. Smirnov
Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia
e-mail: kobtsev@lab.nsu.ru

Received September 30, 2003

Abstract—Soliton self-frequency shift is realized for the first time in a tapered fiber, whose core with a diameter of 2.3 μm is surrounded by air, in the presence of pump pulses with a duration of 55 fs and a wavelength of 805 nm. The self-frequency shift is observed up to a wavelength of 1127 nm. The soliton energy is about 23% of the total energy of the output light pulse. Good agreement between the results of numerical simulation of the soliton self-frequency shift based on the generalized Schrödinger equation and the experimental data is obtained.

1. INTRODUCTION

The effect of continuous low-frequency shift of an ultrashort pulse spectrum with increasing peak power of the pulse known as the soliton self-frequency shift [1–3] makes it possible to generate solitons whose carrier frequency can be tuned in a wide spectral range using the variation in the power of the pump radiation, when its wavelength is in the vicinity of the zero-dispersion point of the medium. Over the last two years, this effect was observed in various photonic-crystal fibers [4]. The soliton wavelength is shifted to 1.26 [5, 6], 1.65 [7], and 1.7 μm [8] in the presence of pumping at wavelengths of 0.81, 1.3, and 1.55 μm, respectively. The soliton self-frequency shift is demonstrated both in conventional photonic-crystal fibers (core diameter 1.9–2.6 μm [5, 6, 8, 9], fiber length 0.8–1.7 m) and tapered holey fiber with a core diameter of 3 μm and a length of 15 cm [7].

In this work, we report on the first observation of the soliton self-frequency shift in a tapered single quartz fiber, whose core with a diameter of 2.3 μm is surrounded by air.

2. EXPERIMENTAL RESULTS

A tapered fiber made of SMF-28 fiber at the Laboratory of Laser Systems, Novosibirsk State University, with the method from [10] was used in the experiments. The sizes of the sample under study are as follows: the fiber waist diameter is 2.3 μm, the waist length is 12 cm, the length of biconical junctions (connecting the original fiber and the waist) is 2.5 cm, and the lengths of the input and output fragments of the original fiber are 5 and 35 cm, respectively.

Figure 1 shows the scheme of the experimental setup. The duration of Ti:Sapphire laser output pulses with a repetition rate of 81 MHz is 50 fs. The mean output power is 380 mW. The spectrum of the laser radiation with an FWHM of 20 nm is centered at 805 nm. Tapered (biconical) fiber is pumped in the spectral range of anomalous dispersion (the zero-dispersion wavelength is 755 nm). Laser radiation passed through the optical system and the Faraday isolator is coupled into the input, undrawn end of the biconical fiber using a $8^{\times}/0.2$ microscope objective. The mean power at the sample entrance is about 110 mW, and the peak pulse power is about 20 kW. The losses inside the samples mainly depend on the shape and the length of fiber fragments with varying diameter. The typical transmittance of the sample is 30–50%. We measure the spectrum of the output radiation in the wavelength range 400–1200 nm with a spectral resolution of 3 nm using an Angstrem automatic spectral analyzer.

To monitor the phase modulation (chirp) of the laser pulses, we employ a two-prism compensator. The output pulses of the femtosecond laser exhibit a small pos-

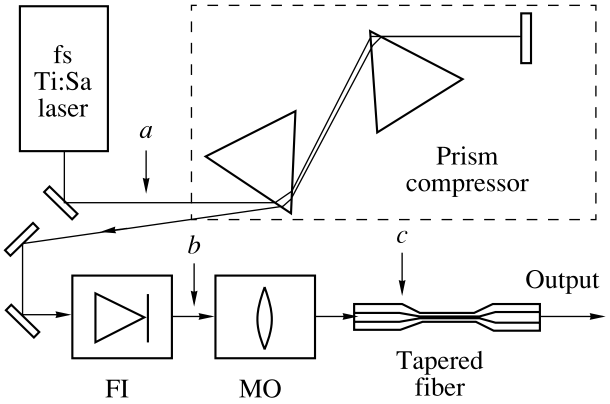

Fig. 1. Experimental setup with a Faraday isolator (FI) and a microscope objective (MO). Pulse duration is measured at points *a*, *b*, and *c*.

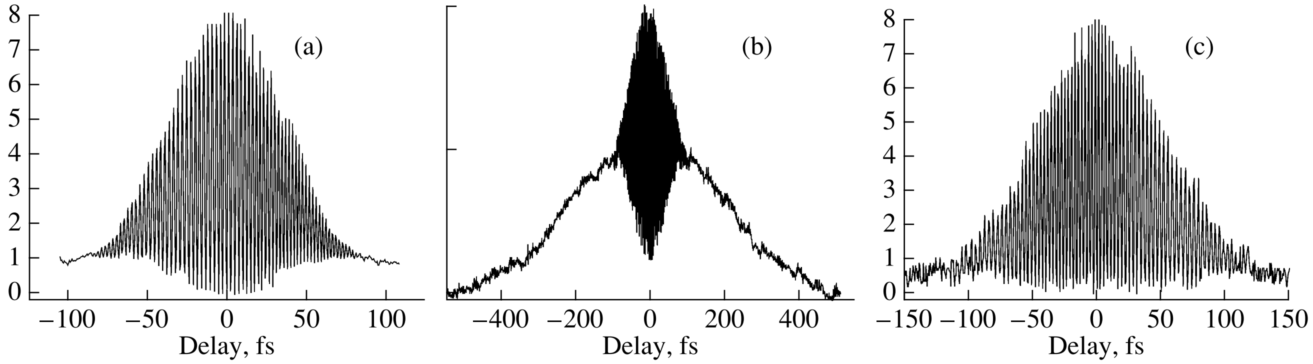

Fig. 2. Interferometric autocorrelation traces of (a) output laser pulses and pulses passed through (b) a Faraday isolator, two-prism compensator, and launch optics and (c) a microscope objective and 10-cm-long fiber.

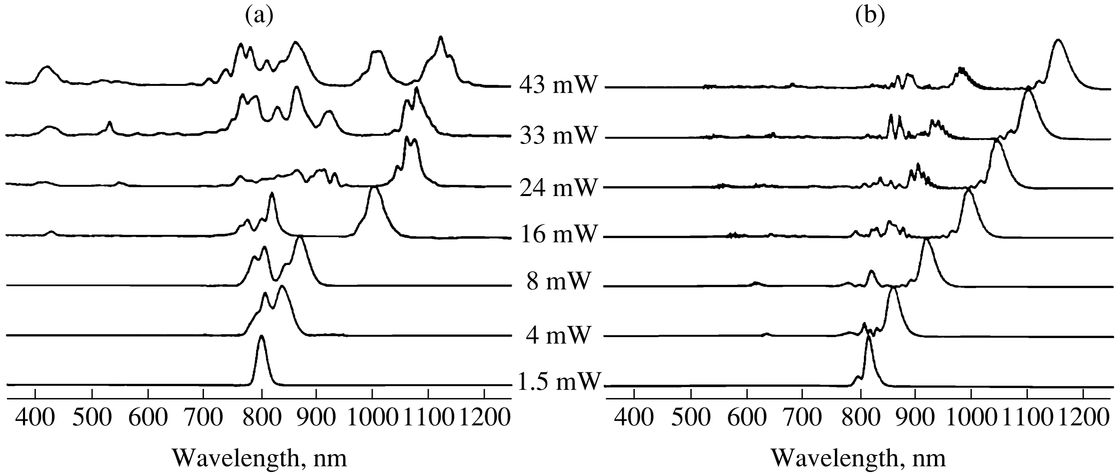

Fig. 3. (a) Experimentally measured and (b) calculated output radiation spectra at various mean output powers.

itive initial chirp that increases when the pulses pass through the elements of the optical isolator, microscope objective, and the starting undrawn fragment of the fiber. The compressor makes it possible to compensate for this positive chirp, so that the pulses arrive to the fiber taper transition with minimum phase modulation. Compressor tuning leads to minimization of the pulse duration immediately in front of the convergent part of the sample. We control pulse duration at three points on the optical path using an autocorrelator (Fig. 1). At points *a*, *b*, and *c*, we measure durations of laser output pulses, pulses passed through a Faraday isolator and compressor, and pulses passed through a microscope objective and an isolated fragment of SMF-28 fiber corresponding to the initial undrawn fragment of the fiber, respectively. Figure 2 demonstrates the autocorrelation function of pump pulses measured at the above three points. The compressor allows for compensation of the developed positive chirp acquired by the pulses passed through the optical elements and the initial fragment of the fiber. Note the similarity of the autocorrelation functions of the output laser pulses and the pulses measured at the entrance of the convergent fragment of the fiber. The pulse duration measured at the entrance of the fiber taper transition is 55 fs. The waist length of the fiber taper transition fiber coincides with the dispersion length of the sample under study (10.8 cm for a pulse duration of 55 fs).

Figure 3a shows experimental spectra of the output radiation for the fiber taper transition fiber under study. When the mean power of the output radiation exceeds 2 mW, we observe splitting of the original spectrum into individual components, which exhibit a red shift with increasing power. If the output power is greater than 10 mW, the generation of single tunable spectral components is supplemented by continuum generation in the blue part of the spectrum, although the power of the continuum radiation is relatively low. When the output power is 16 mW, the energy of the self-frequency-shifted soliton at a wavelength of 1007 nm amounts to 44% of the total energy of the output pulse. A further increase in the pump power gives rise to two isolated spectral peaks at wavelengths of 1014 and 1127 nm. When the total mean power of the output radiation is

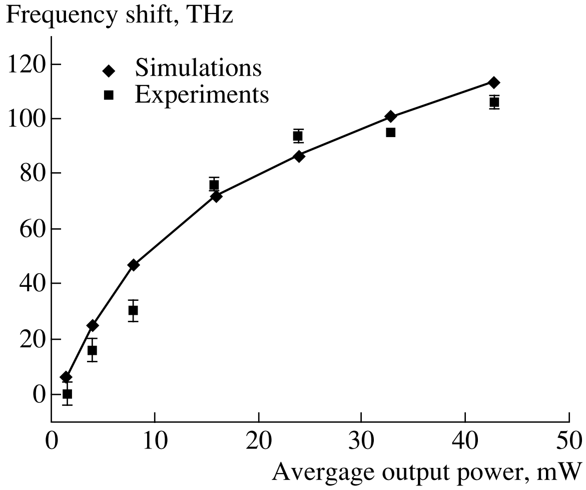

Fig. 4. Experimental and calculated plots of the soliton frequency shift vs. the output radiation power.

43 mW, the mean powers of these spectral components are 7 and 10 mW, respectively.

3. NUMERICAL MODEL

To numerically simulate the experimental results, we use the generalized nonlinear Schrödinger equation from [11] written as

$$\frac{\partial A}{\partial z} = i\sum_{k=2}^{k_{\max}} \frac{i^k}{k!}\beta_k \frac{\partial^k A}{\partial t^k} + i\gamma\left(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\right)\left(A(z,t)\int_0^{\infty} R(t')|A(z,t-t')|^2 dt'\right). \tag{1}$$

Here, $A(z, t)$ is the envelope of the electric field strength, β_k are the dispersion coefficients at the pump frequency ω_0, and $\gamma = n_2\omega_0/(A_{\text{eff}}c)$ is the nonlinear coefficient, where $n_2 = 3.2 \times 10^{-20}$ m^2/W is the nonlinear refractive index of quartz and A_{eff} is the effective area of the fundamental mode cross section. Kernel $R(t)$ of the integral operator of nonlinear response taken from experiments mentioned in [12] contains both electron and vibrational (Raman) contributions.

Equation (1) obtained without using approximation of the slowly varying amplitudes can be used to describe the propagation of pulses whose duration equals a few cycles of the light wave at the corresponding frequency. Equation (1) is derived under the assumption that the radiation propagates inside fiber in only one (fundamental) mode. The validity of this assumption follows from the axial symmetry of the transverse cross section of intensity experimentally measured at the fiber exit. In calculations, we expand the dispersion operator in a Taylor series in terms of frequency up to the term $k_{\max} = 5$. The second addend in the right-hand side of Eq. (1) corresponds to such nonlinear optical effects as the self-phase modulation, self-steepening of the envelope wing, and stimulated Raman scattering (SRS) [11]. In Eq. (1), we do not take into account the linear losses owing to the short (a few tens of centimeters) lengths of the fiber samples under study. These losses lead to exponential decay of the radiation intensity upon propagation along the fiber. Conservation of energy is not fulfilled in Eq. (1), since we take into account the SRS effect. The number of photons is conserved [11, 12].

Figure 3b shows the results of calculations for the drawn fiber with a diameter of 2.3 μm and a length of 12 cm represented as spectra of the output radiation for various pump powers. The analysis of the data presented in Fig. 3 shows qualitative agreement between the experimental results (Fig. 3a) and the results of calculations (Fig. 3b). Each spectrum exhibits an isolated intense long-wavelength peak corresponding to soliton and short-wavelength peaks. Both the experimental data and the results of calculations show that an increase in the pump power leads to a decrease in the soliton carrier frequency and an increase in the number and amplitudes of the short-wavelength peaks. However, note that the experimental intensities of the short-wavelength peaks are higher than the corresponding calculated intensities. In addition, the spectral components that peak at about 420 nm in the experimental spectra measured at output powers of 33 and 43 mW (two upper curves in Fig. 3a) are missing in the results of calculations.

To additionally compare the results of calculations and the experimental data, Fig. 4 demonstrates the dependence of the soliton frequency shift on the output power measured in the experiments. It is seen that there exists good qualitative and quantitative agreement between the experimental and calculated dependences of the soliton frequency shift on the pump power.

4. CONCLUSIONS

We demonstrate soliton self-frequency shift in a single drawn quartz fiber, whose core with a diameter of 2.3 μm is surrounded by air, in the presence of femtosecond pumping. Tapered fiber is pumped by the pulses of a Ti:Sapphire laser with a duration of 55 fs and a wavelength of 810 nm in the spectral range of anomalous dispersion in the vicinity of the zero-dispersion point. The soliton self-frequency shift is observed at wavelengths of up to 1127 nm. The soliton energy amounts to about 23% of the total energy of the output pulse. Numerical simulation of the soliton self-frequency shift based on the generalized Schrödinger equation with allowance for the experimental parameters makes it possible to qualitatively and quantitatively interpret the results obtained.

REFERENCES

1. E. A. Gollovchenko, E. M. Dianov, A. M. Prokhorov, and B. N. Serkin, Pis'ma Zh. Éksp. Teor. Fiz. **42**, 74 (1985) [JETP Lett. **42**, 87 (1985)].
2. F. M. Mitshke and L. F. Mollenauer, Opt. Lett. **11**, 659 (1986).
3. J. P. Gordon, Opt. Lett. **11**, 662 (1986).
4. A. M. Zheltikov, Usp. Fiz. Nauk **170**, 1203 (2000) [Phys. Usp. **43**, 1125 (2000)].
5. I. G. Cormack, D. T. Reid, W. J. Wadsworth, *et al.*, Electron. Lett. **38**, 167 (2002).
6. D. T. Reid, I. G. Cormack, W. J. Wadsworth, *et al.*, J. Mod. Opt. **49**, 757 (2002).
7. X. Liu, C. Xu, W. H. Knox, *et al.*, Opt. Lett. **26**, 358 (2001).
8. F. G. Omenetto, A. J. Taylor, M. D. Moores, *et al.*, Opt. Lett. **26**, 1158 (2001).
9. B. R. Washburn, S. E. Ralph, P. A. Lacourt, *et al.*, Electron. Lett. **37**, 1510 (2001).
10. S. M. Kobtsev, S. V. Kukarin, and N. V. Fateev, Kvantovaya Élektron. (Moscow) **32**, 11 (2002).
11. G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. (Academic, San Diego, 2001; Mir, Moscow, 1996).
12. K. J. Blow and D. Wood, IEEE J. Quantum Electron. **25**, 2665 (1989).