Изв. вузов «ПНД», т.12, № 1-2, 2004

SOLITON COMPRESSION IN DISPERSION DECREASING FIBERS

A.A. Sysoliatin, V.A. Bogatyrjov, S.V. Muraviev

Dispersion decreasing fibers (DDF) have been recognized to be useful for efficient soliton pulse compression. High-quality pulse compression has been obtained in DDF and the input power requirements are significantly lower than that for soliton- effect compression. The maximum compression factor is determined by the ratio of input to output dispersion and typically limited to about 20. Using DDF with optimum dispersion profile it is possible to obtain pedestal-free pulses of less than 200fs duration.

There are several techniques to compress optical pulses, in particular it is possible to utilize soliton effects. Earlier research focused on using the compression of high-order solitons. This can provide rapid compression but suffers from residual pedestal. Furthermore, the pulse quality at the optimum point of compression is poor, since a significant proportion of the pulse energy is contained in a broad pedestal. A less rapid technique but with better pulse quality is adiabatic amplification of fundamental solitons. To avoid pulse distortion the amplification per soliton period cannot be too big. The method to vary dispersion along the fiber length can be used to obtain the same effect as adiabatic amplification, but the effect can be achieved in a passive fiber.

For optical soliton, a small dispersion varying perturbs soliton in the same way as an amplification or loss. The fibers with varying dispersion can have a lot of application in the soliton propagation control. Improved pulse quality with minimal or no pedestal component can be achieved by the adiabatic compression technique using dispersion decreasing fibers (DDF). High-quality pulse compression is possible and the input power requirements are significantly lower than that for soliton-effect compression. The maximum compression factor is determined by the ratio of input to output dispersion and typically limited to about 20. Using DDF with optimum dispersion profile it is possible to obtain pedestal-free pulses of less than 200fs duration.

In general, the single mode fibers with dispersion varying along the length are attracting a considerable attention due to their value for soliton control and propagation. Whether the group velocity dispersion (GVD) decreases exponentially along the fiber length the fundamental optical soliton can propagate without broadening in this medium [1]:

$$\beta_2(z) = \beta_2(0)\exp(-\xi z) \tag{1}$$

where ξ is loss parameter. The varying along length dispersion is eqivalent to amplification from mathematical point of view. One is able to compensate the influence of optical loss in real fiber varying a chromatic dispersion along the fiber length. The numerical simulations are showing that, if in real fiber with loss 0.2dB/km the optical soliton doubles after a propagation on 30km, in the case of the fiber with varying along length dispersion one may propagate without broadening up to 90km.

The practical way to develop fibers with varying dispersion had been established [2]. This method performs a precise control of the fiber core diameter during the drawing. This technology became possible owing to digital signal processing used for the control of the drawing process. At present fibers with various dispersion functions can be produced. In particular DDF have been using successfully for soliton compression and soliton train generation. The method to draw fibers varying along the length from standard preform had been developed. The length of fiber with varying dispersion may be in the range from several meters to several kilometers. The dispersion deviation from the prearranged value is less than 0.1ps/nm/km.

Tailoring the dispersion along the fiber length could not only prevent loss-induced soliton broadening, but also perform pulse compression. In a DDF of a certain length, the dispersion is monotonically and smoothly decreased from an initial value to a smaller value at the end of the length in accordance with some specified profile. Usually the optimum fiber length to achieve the adiabatic compression is a few dispersion length Z_0, defined in terms of the pulsewidth, T_{FWHM} (full width at half maximum or FWHM), and GVD parameter β_2 (ps^2/km):

$$Z_0 = T^2_{\mathrm{FWHM}}/(3.11|\beta_2|). \tag{2}$$

The required pulse peak power increases in proportion to the square of the soliton order. The peak power required for the formation of Nth order soliton is:

$$P_N = N^2/(\gamma Z_0), \tag{3}$$

where γ is the fiber nonlinearity coefficient in units of W^{-1}km^{-1}.

For a DDF with length L the ratio of input to output dispersion determines the maximum pulse compression factor for the case of no fiber loss and a constant nonlinearity coefficient:

$$W_{\mathrm{eff}} = \beta_2(0)/\beta_2(L). \tag{4}$$

The compression experiments have been carried out to confirm the theoretical predictions. The experimental setup included a light source, the EDFA and DDF. The light source was an actively mode-locked fiber laser, which outputs the 2ps fundamental solitons at a center wavelength of 1551nm and repetition rate of 10.496GHz. The DDF length was 1km and its dispersion value changes linearly from 10 to 0.5ps/nm/km. The autocorrelations and spectra of output pulses after DDF (1km length, input pulse of 2ps) are illustrated in Figures 1-2. The average power on DDF input P_{in} was changing from 100 to 240mW.

One should take into account the dispersion profile, i.e. dispersion function along the DDF length, to achieve both high-quality pulse compression and a large compression factor. Earlier experimental works have insisted upon using a hyperbolic dispersion profile since adiabatic soliton pulse compression in this case is expected to be linear. However, numerical simulations and consideration of the higher order effects indicate that the linear and Gaussian dispersion profiles are nearly optimum to obtain efficient pulse compression, especially for subpicosecond pulse compression. High-quality compression with compression factors over 50 can be achieved by launching pulses with input soliton order $1<N<2$ into a DDF with an approximate length equal to one soliton period. On the other hand, soliton-effect compression in fibers with constant dispersion can achieve comparable compression factors of 40, however, a much higher input soliton

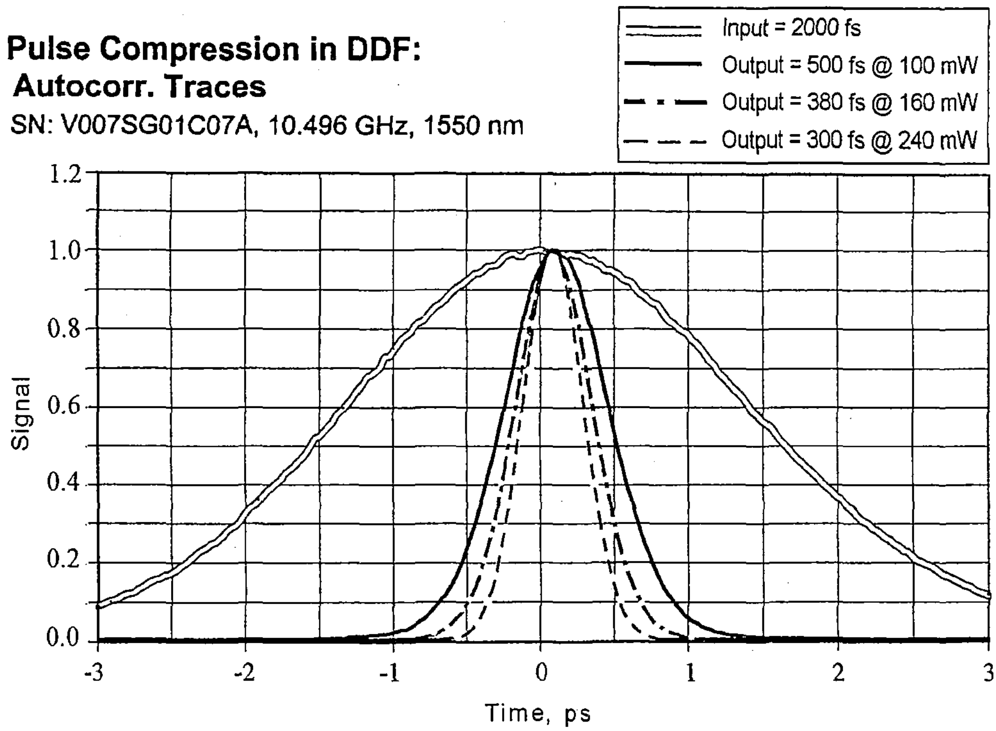


Fig. 1. Autocorrelation plots, input pulse 2ps

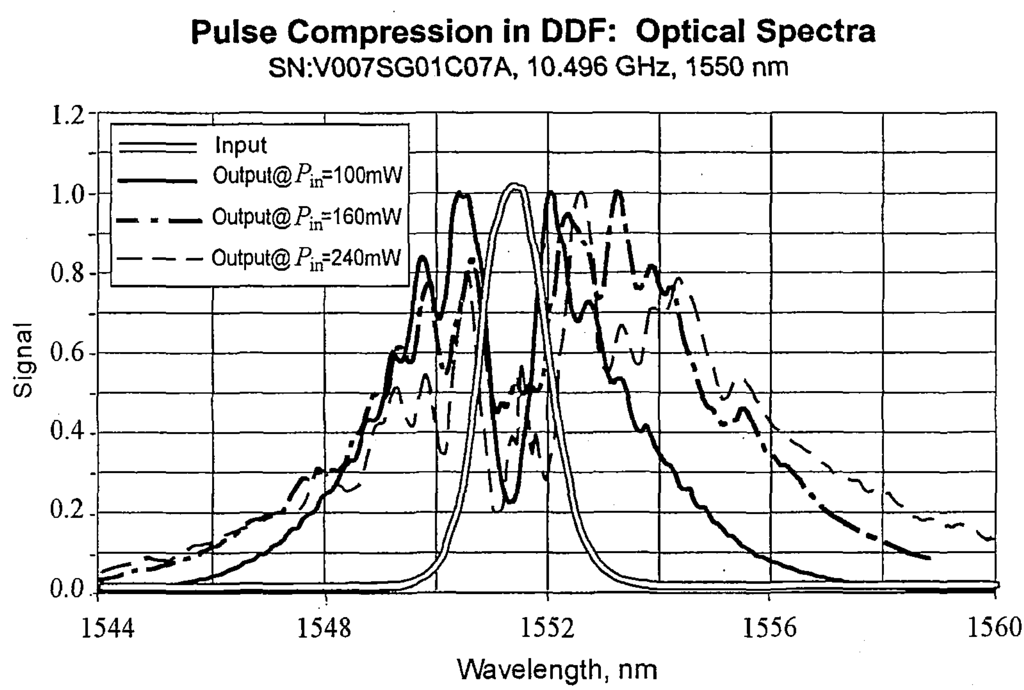


Fig. 2. Optical spectra of compressed pulses

order of N=10 is required. It means significantly higher peak power requirements from the pulse source and approximately 70% of output energy contained in the pedestal component, i.e. the pulse quality in this case is poor. It had been shown that higher order soliton pulse compression in DDF can achieve both high-quality compression and large compression factors [3]. In comparison with the adiabatic compression of a fundamental soliton, the required DDF length is significantly less and much larger compression factors can be achieved. The pulses of 15ps can be compressed down to 200fs using practical fiber lengths (<3km).

In the case of short (<3ps) solitons it is necessary to take into account the higher-order nonlinear and dispersive effects. In particular intrapulse Raman scattering results to the shift of the soliton mean frequency. This frequency shift leads to the change in GVD due to third-order dispersion β_3. These effects result to the soliton corruption. However the stable compression of ultrashort solitons in DDF can take place in the presence of the Raman effect and third order dispersion.

Theory and experiments point to the purposefullness of the application of longitudinally inhomogenous fibers in various areas: input and output of radiation, shaping of the radiation wavefront in graded-index fibers, fiber sensors, optical amplifiers (such fibers allow spontaneous emission to be decreased and thereby the gain raise), femtosecond pulse compression in the infrared and visible region. In particular, multi-soliton fission and quasi-periodicity were predicted in fibers a periodically modulated dispersion [4].

The soliton pulse compression in DDF can achieve both large compression factors and high quality compression. The dispersion profile of the DDF is an important design consideration. In comparison with the soliton-effect compression in fibers with constant dispersion, comparable compression factors can be achieved with significantly lower power requirements. To design the proper dispersion profile along the span length the dispersion slope and mode size changes should be taken carefully into account. The approach to control the chromatic dispersion along the fiber length has the practical advantage of providing optical soliton stability in a way that is completely automatic and passive.

References

1. *Tajima K.* Compensation of soliton broadening in nonlinear optical fibers with loss // Opt.Lett. 1987. Vol. 12. P. 54.

2. *Bogatyrjov V.A., Bubnov M.M., Semjenov S.L. and Sysoliatin A.A.* Length-varying computer-controlled fibre drawing // Measurement Science Technology. 1994. Vol. 5. P. 1370.

3. *Pelusi M.D. and Liu H.F.* Higher order soliton pulse compression in dispersion-decreasing optical fibers // IEEE Journal of Quantum Electronics. 1997. Vol. 33. P. 1430.

4. *Bauer R.G., Melnikov L.A.* Multi-soliton fission and quasi-periodicity in a fiber with a periodically modulated core diameter // Optics Communications. 1995. Vol. 115. P. 190.

Fiber Optics Research Center at the GPI, RAS
Institute of Applied Physics, RAS

Received 13.11.2003

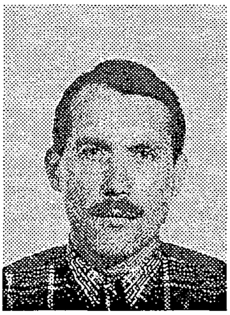
The paper includes main results published at first in the Proceedings of the International Symposium «Topical Problems of Nonlinear Wave Physics», Nizhny Novgorod, Russia, 6-12 September, 2003, 2-61, p. 235.

УДК 621.396.22.029.7

СЖАТИЕ ОПТИЧЕСКИХ СОЛИТОНОВ В СВЕТОВОДАХ С УМЕНЬШАЮЩЕЙСЯ ПО ДЛИНЕ ДИСПЕРСИЕЙ

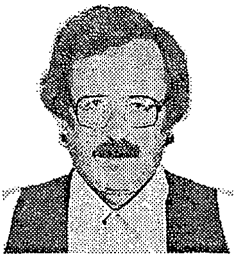
А.А. Сысолятин, В.А. Богатырев, С.В. Муравьев

Световоды с изменяющейся по длине дисперсией представляют собой эффективный инструмент для сжатия оптических импульсов пикосекундной и субпикосекундной длительности. В этих световодах возможна компрессия с высоким качеством, в то же время требования к уровню мощности существенно ниже, чем для метода солитонного сжатия. Максимальный коэффициент компрессии определяется отношением величин дисперсии на входе и выходе и обычно его значение не более 20. В световодах с оптимальным профилем дисперсии по длине можно получить импульсы без пьедестала длительностью менее 200фс.

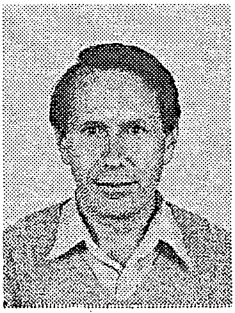


Sysoliatin Alexej A. was born in Novosibirsk, Russia, in 1958. He received the B.S. degree in physics from S.Petersburg Electrotechnical University, in 1981 and the Ph.D. degree from General Physics Institute of Russian Academy of Sciences, Moscow, in 1995. His current scientific interests include nonlinear wave propagation, soliton transmission systems, design and technology of fibers with varying along length chromatic dispersion.

E-mail:alexs@fo.gri.ru



Bogatyrjov Vladimir A. was born in the USSR on May 29, 1949. In 1972 graduated from the Moscow Physical-Technical Institute. From 1972 to 1982 he was with P.N. Lebedev Physical Institute. His early works were connected with the investigation of high power neodymium lasers. Since 1982 his research interests lie in the technology of specialty fibers, including the metal coated optical fibers.



Muraviov Sergey V. was born in March 1955 in Kirov, Russia (USSR). He entered the Radiophysical Faculty of the Gorky State University in 1974 and graduated from the Department of Statistical Radiophysics in 1979. Since 1979 he has been on the radioelectronic engineer staff of the Institute for Radiotechnique in Nizhny Novgorod. Since 1988 he has been on the leading optoelectronics engineer staff of the Institute of Applied Physics (IAP) in Nizhny Novgorod, which belongs to the Russian Academy of Sciences. His current research interests include nonlinear optics, laser - matter interactions, including the generation and application of UV harmonics of Nd:YAG laser radiation for irradiation of polymers and inorganic glasses.