A Single-Mode Fiber with Chromatic Dispersion Varying Along the Length

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***Abstract*—A method for fabrication of a new type of optical fiber with dispersion varying along the fiber length is described. The main optical parameters of a drawn fiber are theoretically studied and experimentally measured. These fibers are of great interest for nonlinear fiber optics. Such applications of the fibers, such as high-quality soliton pulse compression, soliton pulsewidth stabilization through compensation of losses, and generation of a high-repetition-rate train of practically uninteracting solitons, are considered.**

I. Introduction

SINGLE-MODE fibers with chromatic dispersion varying along the length are promising mediums for nonlinear fiber optics. The reason is that the nonlinear light propagation in optical fiber is defined by the interplay of the dispersion and nonlinear effects. Optical soliton is a result of the canceling of the effect of pulse broadening through second-order dispersion by the refractive-index nonlinearity. For optical soliton, a small dispersion varying perturbs soliton in the same way as an amplification or loss. Therefore, fibers with chromatic dispersion varying can have a lot of application in the soliton propagation control.

Fibers with slowly decreasing dispersion (FSDD) realize a regime of effective amplification of solitons [1]–[8]. Tajima [1] was the first to suggest utilizing FSDD in nonlinear fiber optics. He suggested using such fibers for the compensation of the soliton broadening in lossy fibers. Kuehl [2] considered a more general case of the soliton propagation on an axially nonuniform optical fiber. In [3], [7], [8] it was suggested to use FSDD for a generation of high-repetition-rate (GHz–THz) soliton trains. In [5], [8] this method was experimentally realized and a 0.2-THz soliton train was generated. In [3], [4], [18] fibers with slowly decreasing dispersion were used for adiabatic femtosecond soliton pulse compression. We were the first to produce such fibers, which were then used in the experiments [3]–[5], [8], [18].

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To produce dispersion variation, one should fabricate a fiber with varying parameters along the length. Among the fiber parameters, which affect the dispersion, are the chemical composition of material, the fiber refractive-index profile, and the fiber core diameter. From a modern technology point of view, the variation of the first two is a very difficult problem, but the core diameter variation can be produced by varying the speed of fiber drawing from a preform. The fiber core diameter can effectively influence the fiber dispersion only in the spectral region near the zero material dispersion point ($\lambda \approx 1.3$ μm). This is the key idea of our method. The drawing speed was controlled by a program. The program took into account the calculated dependence of fiber dispersion on fiber core diameter for the measured profile of the preform and the desirable dispersion dependence on the fiber length.

In this paper we describe the fabrication and optical properties of fibers with dispersion varying along the length. We also consider some of applications of these fibers in nonlinear fiber optics, such as the compensation of the soliton broadening in lossy fibers, high-quality adiabatic soliton pulse compression, and generation of high-repetition-rate trains of uninteracting soliton pulses.

II. Fiber Fabrication

It is well known, that the total chromatic dispersion D can be approximately expressed as

$$D = M_m + M_w \tag{1}$$

where M_m is a material dispersion and W_w is a waveguide dispersion.

The material dispersion depends on the fiber parameters only slightly, and the effective total dispersion variation can be achieved through waveguide dispersion variation. The waveguide dispersion can be expressed as

$$M_w = \frac{\Delta n}{c\lambda} V \frac{d^2(BV)}{dV^2}. \tag{2}$$

Here Δn is the index difference, B and V are the normalized propagation constant and frequency, respectively. As it can be seen, the variation of the index difference along the fiber length results in dispersion variation. However, in this case it is necessary to obtain the controlled sharp change of GeO_2 concentration along the preform length. This procedure is too difficult. It is easier to vary the V parameter and the value of $d^2(BV)/dV^2$. Variation of the V parameters can be caused by the core diameter variation, which can be achieved through controlled variation of the outer fiber diameter while drawing. This exact method was used in our case.

We were interested in effective dispersion variation at $\lambda = 1.3$–$1.6\ \mu$m. These wavelengths are of great interest for nonlinear fiber optics, because of the minimum optical loss and the negative group velocity dispersion in this region. Dispersion variations from approximately 15 ps/nm/km to zero in the single-mode regime can be achieved at $\lambda = 1.55\ \mu$m by using our method.

The preform for the dispersion shifted fiber should be used. To control the dispersion variation the relation between the chromatic dispersion and outer diameter have been obtained through numerical solution of the scalar-wave equation for the preform profile and fixed drawing coefficient. Calculated dependencies of chromatic dispersion on outer diameter at three wave lengths are shown in Fig. 1 for a typical preform profile of dispersion shifted fibers (see Fig. 2). The chosen region of the outer diameter variation is from 115 to 175 μm. Further increasing of the diameter leads to the appearance of a first higher mode. Decreasing of the diameter less than 115 μm causes excess radiation loss, while into this region the fiber losses are not practically changed. Therefore, using this region is optimum, and we will call it the "working region."

We will describe the fabrication of the fiber which was used in the experiment [5], [8]. The fiber of length 0.9 km was required with dispersion decreasing at wavelength 1.55 μm as

$$D(z)\,[\text{ps/nm/km}] = 10/(1 + 12\, z[\text{km}]). \qquad (3)$$

And the last 100-m fiber had the constant dispersion equal to $D(0.9)$, so that the total fiber length was 1 km. The region of dispersion variation was from 10 to 0.8 ps/nm/km (Fig. 3).

For this purpose, a conventional MCVD triangular profile preform was taken for the fabrication of the fiber. The P101 preform profile is shown in Fig. 2. The necessary length dependence of the outer diameter was calculated using the method described above. Fabrication of the fiber with varying outer diameter requires the special drawing conditions. This fiber was drawn by a machine with a graphite resistance furnace. The drawing process was controlled by the digital feedback system with an adaptive regulator based on computer PDP-11. The measurements of the fiber diameter during the drawing were carried out by a shadow graph control diameter system with the scan rate of 400 Hz. The diameter measurement accuracy of less than 0.1 μm was achieved by the averaging of 80 scan.

For the analysis of the drawing process, it is important to take into account the low- and high-frequency diameter

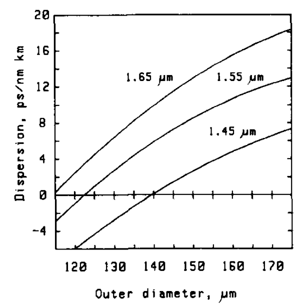

Fig. 1. Calculated chromatic dispersion dependencies on the outer fiber diameter.

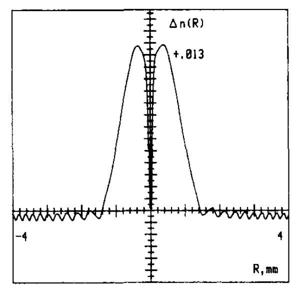

Fig. 2. The P101 profile of the used preform.

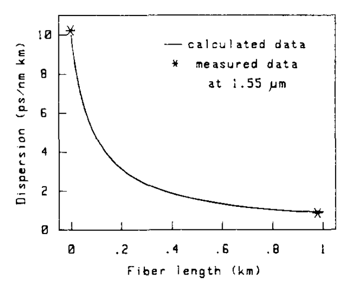

Fig. 3. Calculated length dependence of dispersion and measured.

noise sources [9]. Different digital approaches were used for the signal processing, including the Bessel filter of 6th order, fast Fourier transform for the spectral analysis, the recursive estimation, and modeling. The drawing process was identified in real-time using the recursive least squares method. The analysis of this identification results allowed us to design the adaptive digital control system for the fiber diameter monitoring during the drawing. In the regime of fiber diameter stabilization this control system supported of less than 0.5-μm fiber diameter variation even for the increase of the pulling speed by an order of magnitude during several minutes. The diameter feedback system that we developed permits us to control the fiber diameter according to the determined function $d = d(z)$. The fiber diameter measurement unit is situated by the distance L lower than the hot zone in the furnace. Due to

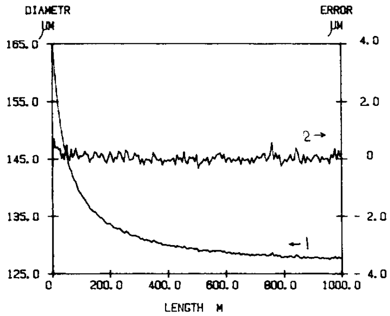

Fig. 4. Dependencies of outer fiber diameter (1) and drawing error (2).

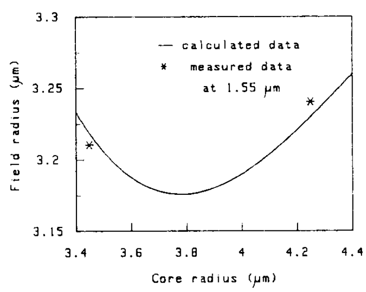

Fig. 5. Calculated mode field radius dependence on core radius.

this fact there is some varying transport delay $T = L/u$ (where u is the pulling speed) in all the fiber drawing feedback systems. This varying transport delay produces a lot of problems for the identification procedure and fiber with dispersion varying drawing. We solved this problem by including additional software delay in the control loop. The additional delay is FIFO (first in, first out), its length is defined currently by the speed u. The FIFO delay in the feedback loop simplifies the design of the control system. The length dependence of the fiber diameter and the error (the difference between this length dependence and equation (3)) on the fiber length are shown in Fig. 4. It can be seen from this picture that the diameter variation of the fiber assigned by (3) is less than 0.5 μm for all the 1-km length. The adaptive digital control system we developed permits us to produce the fiber with a more complicated dependence of outer diameter along length.

Main optical properties were tested in the drawn fiber. The experimental dispersion values at the two fiber ends measured by the interferometric technique are depicted in Fig. 3. As it can be seen, the calculated and measured values are in a good agreement. The optical loss in the fiber amounted to 0.4 dB/km at 1.55 μm. Calculated and measured values of the mode field radius versus fiber core radius are shown in Fig. 5. The core radius is defined on the level of 10% of maximum refractive index, and mode field radius is determined using Gaussian approximation. One can see that the mode spot size is not considerably influenced by the variation of the fiber diameter.

III. Nonlinear Properties and Applications of Fibers with Varying Dispersion

The fibers with axially nonuniform dispersion properties are very useful for the applications in nonlinear fiber optics. Nonlinear propagation of light signals in a fiber is defined by combined action of the self-phase modulation and group velocity dispersion effects [10]. By varying the dispersion one can vary the relation between these effects and, therefore, influence the pulse propagation.

Propagation of an optical signal in a monomode fiber with the slowly axially nonuniform parameters is described by the following equation [2]:

$$\begin{aligned} i\left(\frac{\partial A}{\partial z} + k_1(z)\frac{\partial A}{\partial t}\right) - \frac{1}{2}k_2(z)\frac{\partial^2 A}{\partial t^2} \\ + \omega_0 n_2 G(z)/c|A|^2 A + i\Gamma(z)A = 0 \\ \Gamma(z) = \Gamma_0(z) + \frac{\partial F/\partial z}{2F}, \\ G(z) = \iint |U|^4\,dx\,dy \Big/ \iint |U|^2\,dx\,dy \\ F(z) = n\iint |U|^2\,dx\,dy. \end{aligned} \tag{4}$$

This equation is obtained in the slowly varying amplitude approximation for the electric field $E(t, x, y, z) = A(t, z)U(x, y, z)\exp\{i\int_0^z k_2(z')\,dz' - i\omega t\}$. Here $A(t, z)$ is the electric field amplitude, $U(x, y, z)$ is the function of transverse distribution of the electric field in fiber, k is the wave number, and $k_i = \partial^i k/\partial\omega^i|_{\omega=\omega_0}$, $k_2 = \lambda_0^2 D/(2\pi c)$ is the group velocity dispersion. We take the values F, G, k, k_1, k_2, Γ_0 to be slowly axially change.

Now we introduce the characteristic time of our signal t_0 (for pulses, it's pulse duration (FWHM)), characteristic length $z_0(z) = 0.322\,t_0^2/|k_2(z)|$ (dispersion length) and amplitude $A_0(z) = \sqrt{ct_0^2/(k_2(z)\omega_0 n_2 G(z))}$. Equation (4) is written in dimensionless values

$$\Psi = A(z, t)/A_0(z), \qquad \xi = \int_0^z [1/z_0(z')]\,dz',$$

$$\tau = \left(t - \int_0^z k_1(z')\,dz'\right)/t_0$$

as follows:

$$\begin{aligned} i\frac{\partial\Psi(\xi,\tau)}{\partial\xi} + \frac{\partial^2\Psi(\xi,\tau)}{\partial\tau^2} \\ + |\Psi(\xi,\tau)|^2\Psi(\xi,\tau) - i\gamma(\xi)\Psi(\xi,\tau) = 0 \\ \gamma(\xi) = \gamma_0(\xi) + \gamma_{\text{eff}}(\xi) \\ \gamma_0 = -\Gamma_0 z_0,\ \gamma_{\text{eff}} = -\frac{\partial F/\partial z}{2F} - \frac{\partial k_2/\partial z}{2k_2} + \frac{\partial G/\partial z}{2G}. \end{aligned} \tag{5}$$

Equation (5) is a well-known amplified nonlinear Schrodinger equation [11], but the amplification coefficient depends on the axial coordinate. As a result we have obtained the important fact that the influence of variation of all fiber parameters can be formally considered as an effective amplification.

We divided the full effective amplification coefficient $\gamma(\xi)$ on two parts γ_0 and γ_{eff}. γ_0 is the amplification coefficient associated with an actual change of the signal energy. It is defined by the fiber losses. And γ_{eff} is the effective amplification coefficient, it characterizes the amplification only in the frame of (5) and does not change the signal energy. The effective amplification coefficient is defined by the dispersion variation, the variation of function G, that depends on the mode field form, and mode field area. It is useful for the following discussion to introduce the function of the total effective amplification:

$$W_{\text{eff}} = \exp\left(2\int_0^{\xi} \gamma(\xi')\, d\xi'\right)$$

$$W_{\text{eff}}(z) = \frac{k_2(0)}{k_2(z)}\frac{F(0)}{F(z)}\frac{G(z)}{G(0)} \exp\left(2\int_0^{z} \Gamma_0(z')\, dz'\right). \quad (6)$$

It is clear that the effect of the fiber parameters change is described by the value of the total effective amplification. The effective amplification is defined by the ratios of the initial and final values of k_2, G, F.

In the fabricated by our method fiber with dispersion variation, the fiber losses are practically constant in all the "working regions." The fiber-mode profile and area are not significantly changed within the "working region" of outer diameter (see, Fig. 6). G is close to 0.5 and is practically unchanged, and variation of F is within 20%. The main contribution into the effective amplification is made by the dispersion variation. Therefore, these fibers can be referred to as the dispersion varying fibers.

For the applications, it is interesting to estimate the maximum value of the total effective amplification that can be achieved in such fibers. Its value is defined mainly by the minimum value of the dispersion. The last in turn is restricted by the precision of the fiber fabrication. The outer diameter error is about 0.5 μm and, consequently, the dispersion error is less than 0.2 db/km/nm (see Fig. 1). Therefore the maximum total effective amplification can be 60–80. It seems to be enlarged by improving the technology.

General applications of the fibers with varying dispersion are associated with solitons in optical fibers. Solitons exist as a result of canceling of the effect of pulse broadening through the dispersion by the refractive-index nonlinearity in the negative group velocity dispersion spectral region. In the frame of (5) with $\gamma = 0$, there is an exact soliton solution given by

$$\Psi_s(\tau, \xi) = 1/\tau_s \operatorname{sech}(\tau/\tau_s) \exp(i\xi/\tau_s^2). \quad (7)$$

Now we consider some of applications of FSDD. The effect of slowly dispersion decreasing can compensate for the soliton broadening caused by the fiber losses. FSDD

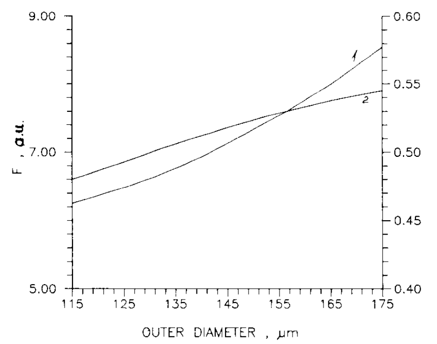

Fig. 6. Calculated dependencies of parameters F(1) and G(2) on the fiber outer diameter.

can be also used for the adiabatic soliton compression and in other cases instead of an actual amplification.

A. Soliton Broadening Compensation in Lossy Fibers

One of the general problems of transmitting solitons through long distances is the optical losses. The effect of fiber losses is in a soliton broadening and, for the large total losses, the soliton is distracted [12]. Among the ways of loss compensation are the Raman amplification [14], [15], the use of active fibers [16]. An advantage of FSDD is that the exact loss compensation can be obtained in every point of fiber. The loss compensation takes place when $\gamma = 0$ in (5) or

$$\Gamma_0 = \frac{\partial F/\partial z}{2F} - \frac{\partial G/\partial z}{2G} - \frac{\partial k_2/\partial z}{2k_2}. \quad (8)$$

Equation (8) determines a law of the drawing process in our method. Supposing only the dispersion variation one can obtained the axial dispersion dependence needed for the soliton broadening compensation [1]

$$k_2(z) = k_2(0) \exp(2\Gamma_0(z)\, dz). \quad (9)$$

In such a fiber, the soliton is not broadening, and it is not disturbing by losses, its amplitude is only decreasing, as it propagates in the fiber. A scheme of a soliton communication line based on FSDD can be as follows [1]. It can consist of many periods. In turn, every period of the line consists of two parts. The first part is a long fiber with the slowly decreasing dispersion according to (9). The second part is a linear amplifier needed for an amplification of solitons to their initial energy. One can estimate the maximum length L_m of FSDD. For the fiber losses 0.2 db/km and the total effective amplification 60, L_m = 90 km.

B. High-Quality Soliton Pulse Compression

Fibers with the slowly decreasing dispersion can be used for soliton compression [2], [4], [17]. The theory is based on (5). The soliton in amplified nonlinear Shrodinger equation is adiabatically compressed if the amplification is adiabatic [11]–[13], that is, the amplification is small on the soliton dispersion length

$$\gamma t_s^2/t_0^2 \ll 1. \tag{10}$$

The soliton pulsewidth decreases according to $t_s(z) = t_s(0) \exp\,(2\int_0^z \gamma(z')\,dz')$. Substituting γ from (5) into this expression, we obtain

$$t_s(z) = t_s(0)W_{\text{eff}} \tag{11}$$

where W_{eff} is given by (6).

The condition for the dispersion change to be adiabatic is

$$\frac{t_s^2}{k_2}\frac{\partial k_2}{\partial z} \ll 1. \tag{12}$$

This theory is valid for picosecond solitons. The maximum compression is equal to the maximum effective amplification, which can be obtained, is about 40–60 as we have estimated above. For femtosecond solitons, the picture is complicated by the higher order dispersion and Raman self-scattering effects. As a result, a femtosecond soliton behavior in FSDD differs from the case of picosecond solitons [17], [18]. A compression of 130-fs soliton to 50 fs has been experimentally obtained in FSDD [4], [18]. In [16] a compression of optical solitons to approximately 20 fs in FSDD has been theoretically predicted.

C. Generation of a High-Repetition-Rate Periodic Train of Uninteracting Solitons

In [3], [5], [7], [8] it has been shown that by using an adiabatic amplification of sinusoidal signal a train of uninteracting solitons at a high repetition rates (GHz–THz) can be produced. The key idea is that under amplification of a weak optical signal having a sinusoidal envelope (a bit signal of two separated frequencies) in a fiber the signal is reshaping into solitons without a pedestal due to the joint action of the self-phase modulation and dispersion effects. Solitons do not interact with each other because there is no pedestal and the separation among the solitons is large. A case of a constant gain along the fiber was considered in [3], [5], [7], [8]. Equally, instead of the actual amplification, FSDD can be used. A constant effective gain Γ in FSDD takes place in the case when the dispersion varyation is given by

$$k_2(z) = \frac{k_2(0)}{1 + 2\Gamma z}. \tag{13}$$

The fiber described in the present paper (see Section II) had such a dispersion dependence on the length (3) and was specially designed and fabricated exactly for the soliton train generation. A 0.2-THz train of 0.5-ps solitons was generated [5], [8].

IV. Summary

In this paper, we presented the first report describing a method for the fabrication of a new type of optical fiber with dispersion varying along the fiber length. The main parameters of fabricated fibers are theoretically studied and experimentally measured. These fibers are of great interest for nonlinear fiber optics. We shown that all variations of the fiber parameters can be treated as an effective loss or gain. We described such applications of these fibers as the high-quality adiabatic soliton compression, compensation of soliton broadening in lossy fibers, generation of high-repetition-rate periodic soliton trains of rarely interacting solitons. Our fibers with slowly decreasing dispersion fabricated by the described in this paper method have been used in the nonlinear fiber-optics experiments.

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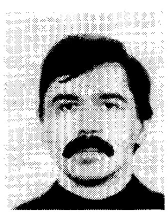

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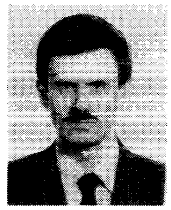
A. M. Prokhorov, photograph and biography not available at the time of publication.



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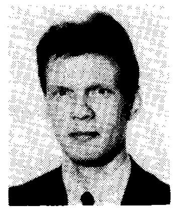

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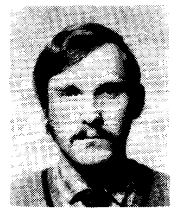

Sergey L. Semenov was born in Zagorsk, Russia, on December 21, 1958. In 1982 he graduated from the Moscow Physical Technical Institute.

Since 1982 he has been employed by the Fiber Optics Department of the General Physics Institute, the Academy of Sciences of the USSR. He dealt with optical fiber fabrication and improving fiber strength. His current activities have focused on mechanical properties (strength and fatigue) and reliability of silica glass and fibers.

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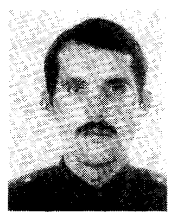

Alexej A. Sysoliatin was born in Novosibirsk, USSR, in 1958. He graduated from Leningrad Electrotechnical Institute in 1981. He joined General Physics Institute of the USSR Academy of Sciences in 1984. Since then he has worked in the area of technology of optical fibers fabrication. His current research interests include the digital signal processing and computer-aided control systems in investigations on drawing technique.

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Stanislav Chernikov was born in Moscow, Russia, on May 24, 1966. He graduated from the Moscow Physical and Technical Institute with Honors in 1989 and received the B.S. degree in physics.

Since 1989 he has been with Fiber Optics Department of the General Physical Institute of Academy of Sciences of the USSR, Moscow, and currently he is a Research Fellow. His Ph.D. thesis concerns the theoretical and experimental study of the methods of a high-repetition-rate soliton train generation in optical fibers suitable for the soliton transmission systems. His research interests include a soliton propagation in fibers with slowly decreasing dispersion, ultrafast optical pulse generation and propagation, and the Raman effect in optical fibers.

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A. N. Gur'yanov, photograph and biography not available at the time of publication.

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G. G. Devyatykh, photograph and biography not available at the time of publication.

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S. I. Miroshnichenko, photograph and biography not available at the time of publication.