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FORMATION THE PIECOSECOND OPTICAL PULSES OF THE ASSIGNED STRUCTURE USING PRECISION LINES OF DELAY

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ФОРМИРОВАНИЕ ПИКОСЕКУНДНЫХ ОПТИЧЕСКИХ ИМПУЛЬСОВ ЗАДАННОЙ СТРУКТУРЫ С ИСПОЛЬЗОВАНИЕМ ПРЕЦИЗИОННЫХ ЛИНИЙ ЗАДЕРЖКИ

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ФОРМУВАННЯ ПІКОСЕКУНДНИХ ОПТИЧНИХ ІМПУЛЬСІВ ЗАДАНОЇ СТРУКТУРИ З ВИКОРИСТАННЯМ ПРЕЦИЗІЙНИХ ЛІНІЙ ЗАТРИМКИ

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Abstract. The article examines the development of methods of one to increase the spectral efficiency of the fiber optic systems of transmission. The essence of the method is shown with the use of alphabet as signals with peak modulation and frequency manipulation. On the receiving side, such signals are distinguished by successive application of selective operations on the frequency subcarrier and spectral analysis of the low-frequency envelope of the signal. A short optical pulse with duration of 3-10 ps with a given shape of the low-frequency envelope is formed on the transmitting side.

In order to form such a pulse the method of approximation of a given function with a weighted sum of short pulses of duration about 100 fs is used. With such short functions, it is proposed to use laser pulses in the mode-locking mode. Such pulses have a sufficiently short duration and are approximately Gaussian. To form the output signal, a single laser pulse is divided into several directions (about 100). Further in each direction, the pulse is amplified (or attenuated) in accordance with the necessary amplitude of the readout.

In each direction the pulse is then delayed by the necessary time in the delay line. The output signals from the delay lines are summed and transmitted to the input of the trunk optical fiber. It is shown that this method can be implemented using existing technologies. As a problematic part the creation of a system of delay lines with slightly different delay time is considered. The time difference step is approximately 100 fs. As a method of manufacturing such systems of delay lines, it is proposed to use optical fibers of the same length with a slightly different composition of alloying additives. This method allows regulating the difference in group velocities (group refractive indices) with sufficient accuracy and provides the necessary accuracy of the delay step of the initial pulse. The performed calculations show that the use of the proposed methods makes it possible to substantially increase the throughput of fiber-optic transmission systems using modern technologies for manufacturing optical components.

Key words: refractive index, group refraction index, group velocity, frequency, doping, concentration, structural identification.

Аннотация. Статья посвящена развитию методов повышения спектральной эффективности волоконно-оптических систем передачи. Рассматривается один из методов решения данной проблемы. Суть метода сводится к использованию алфавита сигналов с амплитудной модуляцией и частотной манипуляцией. На стороне приема такие сигналы различаются последовательным применением операций селекции по частотной поднесущей и спектральным анализом низкочастотной огибающей сигнала. На стороне передачи формируется короткий оптический импульс длительностью 3-10 пс с заданной формой низкочастотной огибающей. Для формирования такого импульса используется метод аппроксимации заданной функции взвешенной суммой коротких импульсов длительностью порядка 100 фс. В качестве таких коротких функций предлагается использовать импульсы лазера в режиме синхронизации мод. Такие импульсы имеют достаточно малую длительность и приблизительно гауссову форму. Для формирования выходного сигнала единственный импульс лазера разделяется на несколько направлений (порядка 100). Далее в каждом направлении импульс усиливается (или ослабляется) в соответствии с необходимой амплитудой отсчета. Затем в каждом направлении импульс задерживается на необходимое время в линии задержки. Выходные сигналы с линий задержки суммируются и передаются на вход магистрального оптического волокна. Показано, что данный метод может быть реализован с использованием существующих технологий. В качестве проблемной части рассматривается создание системы линий задержки с незначительно различающимся временем задержки. Шаг различия времени приблизительно 100 фс. В качестве метода изготовления таких систем линий задержки предлагается использовать оптические волокна одинаковой длины со слабо различающимся составом легирующих добавок. Такой метод позволяет с достаточной точностью регулировать различие групповых скоростей (групповых коэффициентов преломления) и обеспечивает необходимую точность шага задержки исходного импульса. Выполненные расчеты показывают, что использование предлагаемых методов позволяет существенно увеличить пропускную способность волоконно-оптических систем передачи при использовании современных технологий изготовления оптических компонентов.

Ключевые слова: коэффициент преломления, групповой коэффициент преломления, групповая скорость, частота, легирование, концентрация, структурная идентификация.

Анотація. Стаття присвячена розвитку методів підвищення спектральної ефективності волоконно-оптичних систем передачі. Розглядається один з методів вирішення цієї проблеми. Суть методу зводиться до використання алфавіту сигналів з амплітудною модуляцією і частотною маніпуляцією. На приймальній стороні такі сигнали розрізняються послідовним застосуванням операцій селекції по частотній піднесучій і спектральним аналізом низькочастотної обвідної. На передавальній стороні формується короткий оптичний імпульс тривалістю 3-10 пс із заданою формою низькочастотної обвідної. Для формування такого імпульсу використовується метод апроксимації заданої функції зваженою сумою коротких імпульсів тривалістю близько 100 фс. В якості таких коротких функцій пропонується використати імпульси лазера в режимі синхронізації мод. Такі імпульси мають досить малу тривалість і приблизно гауссову форму. Для формування вихідного сигналу єдиний імпульс лазера розділяється на декілька напрямів (близько 100). Далі в кожному напрямі імпульс посилюється (чи послабляються) відповідно до необхідної амплітуди відліку. Потім в кожному напрямі імпульс затримується на необхідний час в лінії затримки. Вихідні сигнали з ліній затримки сумуються і передаються на вхід магістрального оптичного волокна. Показано, що цей метод може бути реалізований з використанням існуючих технологій. Як проблемна частина розглядається створення системи ліній затримки з часом затримки, що трохи різняться. Крок відмінності часу приблизно 100 фс. Як метод виготовлення таких систем ліній затримки пропонується використати оптичні волокна однакової довжини із складом легуючих домішок, що не сильно різняться. Такий метод дозволяє з достатньою точністю регулювати відмінність групових швидкостей (групових коефіцієнтів заломлення) і забезпечує необхідну точність кроку затримки початкового імпульсу. Виконані розрахунки показують, що використання методів, що пропонуються, дозволяють значно збільшити пропускну здатність волоконно-оптичних систем передачі при використанні сучасних технологій виготовлення оптичних компонентів.

Ключові слова: коефіцієнт заломлення, груповий коефіцієнт заломлення, групова швидкість, частота, легування, концентрація, структурна ідентифікація.

Introduction. The available frequency spectrum in fiber-optic transmission systems (FOTS) occupies approximately the band from 175 THz to 375 Hz. Thus, the total bandwidth is about 200 THz. How effectively is this frequency resource used?

In modern industrial FOTS of STM-64 type, the data transfer rate in one frequency channel is 10 Gbit/s [1]. Such a frequency channel has a bandwidth of about 100 GHz. In the range of the central wavelength of 1550 nm (about 193 THz), 40 frequency channels are organized. The total data transfer rate is approximately 400 Gbit/s. Thus the spectral efficiency (the ratio of the data transfer rate in bits/s to one hertz of the bandwidth) is about 0.005.

The use of similar frequency plans in the vicinity of several optical carriers (DWDM systems) makes it possible to increase this index by an order of magnitude. The spectral efficiency is approximately 0.05. It is reported [2] that in experimental FOTS the data transfer rate is 20 Tbit/s. The record value of spectral efficiency is, therefore, 0.1. For comparison: in mobile communication systems using CDMA technology this indicator is about 10 units [3]. In 100 times more than for record values in the FOTS!

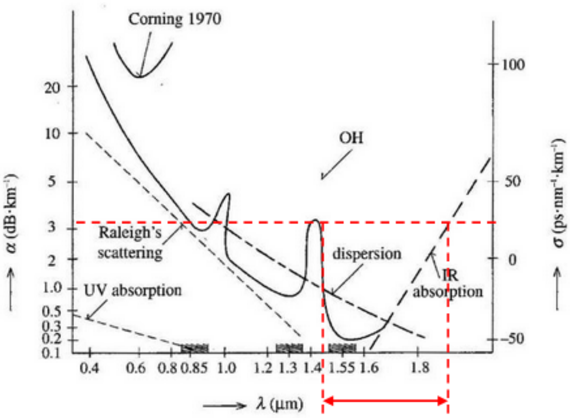

Figure 1 – Typical graph dependence of the attenuation coefficient on wavelength

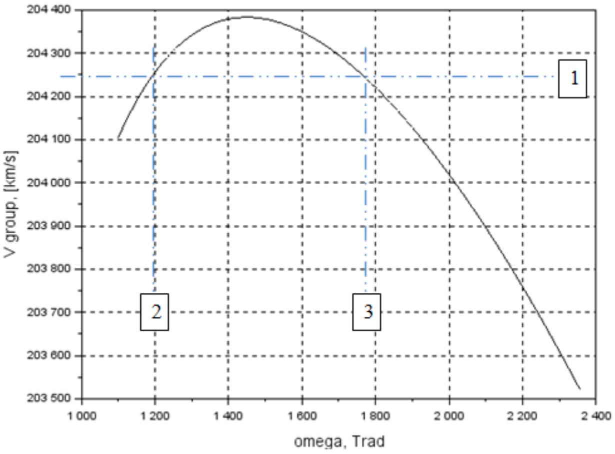

Figure 2 – Equalization of group velocities in logical frequency channels:
1 – line of equal group velocities; 2 – carrier frequency of the forward channel; 3 – carrier frequency of the reverse channel

This result may seem paradoxical. In fact, the FOTS channels are protected from external interference, and the radiation inside the optical fiber (FO) does not affect adjacent channels. The reason for the relatively low spectral efficiency of the FOTS is the presence of different dispersion effects, as well as the dependence of the damping factor on the frequency. Significantly, relatively narrow frequency bands are used for data transmission (Fig. 1) in the vicinity of the so-called transparency windows (in fact, the region of local minima of the dependence of the attenuation coefficient on frequency).

Analysis of the graph in Fig. 1 shows that attenuation in a small vicinity of the 850 nm transparency window is approximately the same as in a very wide vicinity of the 1550 nm transparency window. In the latter case, attenuation at a level of about 3 dB/km is provided in the band occupying about 1/3 of the entire available frequency range. And this "frequency abundance" is practically not used. On the other hand, the application of even elementary compaction methods with the organization of logical channels of equal group velocities (Fig. 2) makes it possible to increase the total transmission rate two times [4]. In this case, two logical channels with the same group speeds can be used for duplex transmission (forward and reverse channel) in the same FO. **The purpose of this article** is the substantiation of the principal possibility of increasing the spectral efficiency of narrow-band FOTS by approximately an order of magnitude under the conditions of the existing level of the technology of manufacturing optical components.

Alphabet of signals. One of the methods for increasing the spectral efficiency of a FOTS is considered in [5]. The essence of the method is to use for the transmission of the signal's alphabet with amplitude modulation and frequency manipulation:

$$E_k(t) = U_k(t)\cos(\Delta\Omega_k\ t)\exp(j\omega_0 t), \quad k = 1...K, \tag{1}$$

where $U_k(t)$ – the envelope of the low frequency component (LFC); k – signal's alphabet; $\Delta\Omega_k$ – low frequency deviation relative to the carrier ω_0; K– the total number of different signals in the alphabet. Note that if $K = 2^N$, then the implementation of the alphabet (1) will increase the data transfer rate in *N* times.

There are no fundamental limitations on the functional form of the LFC. It is important to fulfill two conditions. First, on the receiving side, the signals should be distinguishable. Second: on the receiving side, the effective duration of the signals should not exceed the duration of the clock interval. It follows that the different signals of the alphabet (1) should have approximately the same initial duration and approximately the same expansion due to dispersion in the FO. Otherwise, the duration of the clock interval will determine the maximum duration pulse on the receiving side.

The first condition is fulfilled by the successive application of frequency filtering and subsequent recognition of the energy spectra of the LFC signals. In this case, the transformation from the time representation of the signal to the spectral representation is performed using the grating systems [6]. The second condition is satisfied, in particular, for the alphabet with LFC in the form of Gaussian pulses [4]:

$$U_k(t, z = 0) = \frac{1}{\sigma_k \sqrt{2\pi}} \exp\left(\frac{-t^2}{2\sigma_k^2} \right), \quad k = 1...K, \tag{2}$$

where the condition $z = 0$ means the distribution of the signal energy at the time of propagation along the FO, and the parameter σ_k characterizes the initial effective pulse duration. From the theory of probability, it is known that within the interval $T_k = [-3\sigma_k, 3\sigma_k]$ approximately 97% of the pulse energy is contained. Variation of parameters σ_k and $\Delta\Omega_k$ allow the equalization of the expansion of impulses due to material dispersion. A concrete example of the parametric realization of the alphabets (1-2) is given in Table 1, where $\Delta F_k = \Delta\Omega_k / 2\pi$ – deviation of the cyclic frequency relatively to the carrier; ψ_k – parameter of the effective width of the energy spectrum of the LFC (in this case, about 97% of the energy of the signal in the frequency domain is contained in the interval $\Psi_k = [-3\psi_k, 3\psi_k]$).

Table 1 – Parameters of the system of Gaussian pulses alphabet

k	$\Delta\Omega_k,\ 2\pi \cdot 10^9\, rad/s$	$\Delta F_k,\ GGc$	$\psi_k,\ GGc$	$\sigma_k,\ ps$
1	1,2566E+02	2,0000E+01	8,0000E+01	1,2500E+01
2	1,7771E+02	2,8284E+01	7,4833E+01	1,3363E+01
3	2,1765E+02	3,4641E+01	6,9282E+01	1,4434E+01
4	2,5132E+02	4,0000E+01	6,3246E+01	1,5811E+01
5	2,8098E+02	4,4721E+01	5,6569E+01	1,7678E+01
6	3,0780E+02	4,8990E+01	4,8990E+01	2,0412E+01
7	3,3247E+02	5,2915E+01	4,0000E+01	2,5000E+01
8	3,5542E+02	5,6569E+01	2,8284E+01	3,5355E+01

Based on the alphabet of signals with the parameters from Table 1, it is possible to form a signaling system that allows 256 possible states to be transmitted in one pulse, i.e. one byte. In this case, a separate pulse in the clock interval is formed as a weighted sum of the signals of the alphabet (2):

$$W_m(t) = \frac{1}{\mathrm{A}_m} \sum_{k=1}^{K} \alpha_k^m U_k(t), \quad \mathrm{A}_m = \sum_{k=1}^{K} \alpha_k^m, \quad \alpha_k^m = \begin{Bmatrix} 1 \\ 0 \end{Bmatrix}, \quad m = 0,...,2^K - 1, \tag{3}$$

where α_k^m – expansion coefficients of the number m in the binary system; functions $U_k(t)$ are determined by the dependence (2). The normalizing factor A_m^{-1} s introduced to equalize the energy of the signals of the system $W_m(t)$.

Analysis of the values of the parameters in Table. 1 is shows the signals of system (3) in the frequency domain do not go beyond the band of one frequency channel of FOTS STM-16 or STM-64 (from 100 GHz to 200 GHz). Thus, the signal system (3) basically allows one single byte of information to be transmitted in one pulse, i.e. the transfer rate of the FOTS can be increased by a factor of 8. Frequency filtering of signals spaced at 5-10 GHz is not problematic. A definite scientific and technical problem is forming the envelope of the LFC of a given form. In this case it must be taken into account the order of the initial duration of the optical pulses (1-10 ps, as shown in Table 1).

The method of forming a low-frequency envelope. In this article we confine our consideration to the special case of the LFC envelope in the form of a Gaussian function (2). It is known that in the regime of mode locking [7], laser radiation sources form pulses that are approximately described by functions of the square of the hyperbolic secant form or in the form of a Gaussian pulse. We are also confined by the second case. The generation the pulses of the Gaussian form (2) directly by the laser require a tuning for 100 ps of the effective pulse duration in accordance with Table 1. The solution of this problem is very difficult from a technical point of view. The method of forming the LFC envelope by approximating short functions of readings is promising [8]. A schematic diagram of the device implementing this method is given in Fig. 3. Fig. 4 illustrates the approximation of a long Gaussian pulse with a weighted sum of a sequence of short Gaussian pulses.

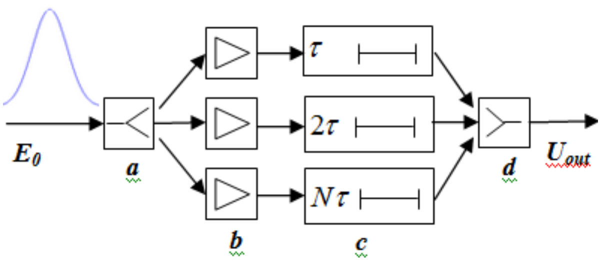

Figure 3 – Schematic diagram of the LFC formation, which implements the approximation by the readings's functions:
a – optical demultiplexer (splitter); *b* – optical amplifiers; *c* – precision delay lines; *d* – optical multiplexer (adder)

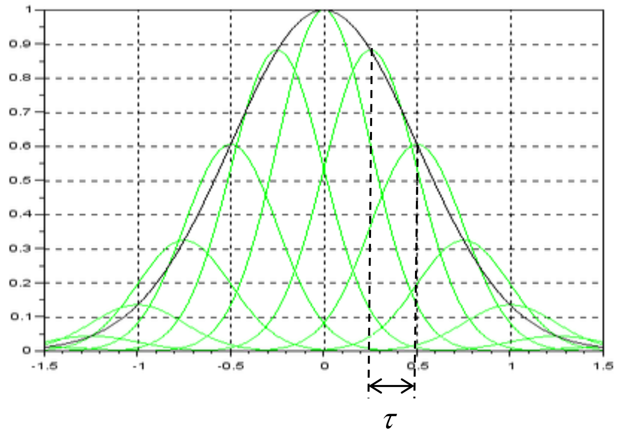

Figure 4 – Approximation of a long Gaussian pulse by a sequence of short Gaussian pulses

The proposed approximation of the alphabet (2) is represented in the following general form:

$$U_k(t,M)=\sum_{m=-M}^{M}\frac{b}{\sigma_k\sqrt{2\pi}}\exp\left(\frac{-m^2\tau^2}{2\sigma_k^2}\right)\exp\left(-\frac{(t-m\tau)^2}{2\beta^2}\right)\to U_k(t),\quad \sigma_k>>\beta\ , \qquad (4)$$

where the dimensional coefficient b is determined by the condition of the maximum rate of convergence of the approximant to the initial function and in general form can be defined as $b=\sqrt{\alpha/\beta}$; τ – the step of samples grid, which is chosen from condition: $M\tau\geq 3\sigma_k$. Selecting the number of M functions of samples in the expression (4) is determined by the necessary accuracy of approximation. It can be shown thet when $M\to\infty$ there is convergence $U_k(t,M)\to U_k(t)$ in the metric L_1 and in equivalent metrics. In this work, we confined by the illustrations (Fig. 5, 6).

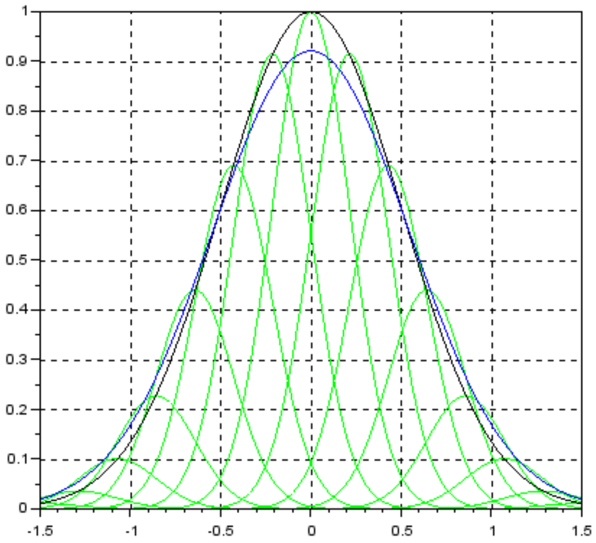

Figure 5 – Approximation by sample functions for M = 7 (total number of samples is 15)

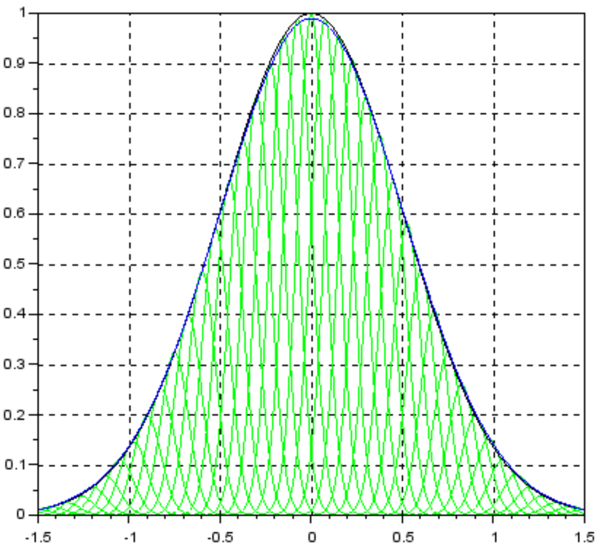

Figure 6 – Approximation by sample functions at M = 20 (total number of samples is 41)

As an indicator of the accuracy of approximation (4), we take the maximum error in the reproduction of the amplitude:

$$\delta U_k = \max\left|U_k(t) - U_k(t, M)\right| / \max\left|U_k(t)\right| . \qquad (5)$$

For $M = 7$ (total number of sample functions $N = 2M + 1 = 15$) indicator value (5) approximately equals to $8{,}5 \cdot 10^{-2}$ (Fig. 5). If $N = 41$ the value of this indicator is $7{,}9 \cdot 10^{-3}$. For the value $N = 101$ the corresponding illustrations are not given, since the graphs of the original function and the approximants are not graphically indistinguishable. The indicator value (5) has order $2{,}4 \cdot 10^{-5}$, which we will assume to be a negligibly small quantity.

Parametric constraints. Beyond the specific parametric model of the FOTS channel, the assigned task does not make sense. Here we confine by considering the case of narrow-band channel with a width of the order of 100-200 GHz (FOTS STM-64 [1]). The duration of the clock interval will be 100 ps. This corresponds to the practical binary alphabet transfer rate (0 or 1 in one clock cycle) of 10 bps, and in the proposed method 80 bps. To estimate the increment of the pulse duration as we propagate along the FO, we take an average value of the material dispersion coefficient of the order of 0,3 – 1 ps/(nm · km). In the vicinity of the transparency window of 1550 nm, the bandwidth of 100 GHz corresponds to approximately 0,8 nm. Thus, with an initial pulse duration of the order of 3 – 10 ps, data can be transmitted without impulses from neighboring clock intervals at a distance of 100 – 300 km. The last estimation fully corresponds to the structure of the regeneration plots in the Ukrainian FOTS.

Aspects of technical implementation. The known devices [9] on the receiving side allow performing of spectral transformations with an accuracy of up to 15 pm. Taking into account the bandwidth of the order of 0,8 – 1 nm, this resolution can be considered sufficient to distinguish the signals of the alphabet (2). The sensitivity of the photodetectors is also sufficient [10]. As shown above, for the realization of signals with duration of the order of 10 ps, 100 samples are sufficient, which will be separated in steps of 100 fs. The sampling functions should also have duration of about 100 fs. The generation of such short pulses is technically feasible. Thus, titanium-sapphire lasers allow the generation of pulses with duration of about 3,4 fs. In this case, the spectrum of such pulses will occupy about 128 THz. Accordingly, a pulse of 100 fs duration will occupy a band of about 4,35 THz. If amplifiers (Fig. 1) use optical amplifiers (OA) of a traveling wave [1], then it is possible to provide an acceptable time for tuning the gain factors – about 1 – 2 ps. In this case, the OA of the traveling wave is sufficiently broadband. Thus, the width of the band at the level of 0,5 is not less than 38 nm. In the vicinity of the 1550 nm transparency window this band corresponds to approximately 4,75 THz, which is acceptable. The operations of dividing the optical signal along the directions and then combining them (positions *a* and *d* in Fig. 1) are performed exclusively by optical components [1]. Such components are not inertial-free and do not distort the waveform except a proportional reduction in power. If necessary, the separation of the signal over several channels can be performed by cascade systems of splitters.

Thus, the fundamental difficulty of technical realization is only the production of a system of delay lines with a relative step of the order of 100 fs.

The system of delay lines with precision pitch. Let's confine by considering the delay lines made of FO. Lines of delay (position *c* in Fig. 1) must satisfy rather harsh conditions.

First, since short sampling pulses occupy a wide band of about 4,35 THz, then significant dispersion effects will appear in the FO. In the case of long lines, even the higher-order dispersion should be taken into account [11]. These effects will appear in lines of great length. Estimating the material dispersion sufficiently large 1 ps/(nm · km) in a 0,8-nm-wide channel, we come to the conclusion that the initial pulse duration of 100 fs can double at a distance of 100 m. If it is considered acceptable to extend the sampling pulse by 1-10 %, then the limiting length of the delay lines will necessarily be limited to 1-10 meters.

Second, the relative delay step is very small (100 fs) and must be maintained with high accuracy in a sufficiently wide frequency range.

A simple method of constructing a system of delay lines is to use segments of FO of the same structure with different physical lengths. Let us estimate the orders of the step length of the OB for this method. The delay in the lines is determined by the formula:

$\Delta t_n = T + n\tau, \quad n = 1...N$. The relative delay step is determined by the dependence:

$$\tau = \frac{L_n - L_{n-1}}{V_{gr}} = \frac{L_n - L_{n-1}}{c} n_{gr} = \frac{\Delta L}{c} n_{gr}, \tag{6}$$

where L_n – physical length of n delay line; V_{gr} – group velocity; n_{gr} – group refractive index; c – light speed in vacuum; ΔL – the difference (step) of the lengths of the FO segments. It follows from (6) that the step length of the FO segments: $\Delta L = \tau \cdot c / n_{gr}$. In the last expression, we take the value $n_{gr} \approx 1{,}5$. Then, at the required relative step $\tau = 100$ fs, the difference in the lengths of adjacent segments of the FO should be approximately 20 μm. Such a difference can be ensured by precise grinding of the ends of the FO. However, it is also necessary to ensure the accuracy of grinding, which should not exceed 1% of 20 μm, i.e. 0,2 μm. Without excluding the possibility of achieving this accuracy, consider an alternative method of producing delay lines, based on the precise alloying of the FO core composition. The refractive index and the group refraction index of quartz glasses have an expressed dependence on the frequency and on the content of alloying additives (Fig. 7, 8). In this case, only the alloying of the basic composition SiO_2 additives of germanium dioxide GeO_2. The method of structural identification [12] of the two-parameter dependence of the group refractive index on the frequency and concentration of alloying additives gives the following model in this case:

$$\begin{aligned} n_{gr}(\omega, \mu) = {} & 1{,}5035\text{E+00} - 6{,}6031\text{E-05} \cdot \omega + 3{,}2447\text{E-08} \cdot \omega^2 - 4{,}6630\text{E-12} \cdot \omega^3 + \\ & + (1{,}2998\text{E-01} + 2{,}1283\text{E-05} \cdot \omega + 7{,}6240\text{E-09} \cdot \omega^2 + 1{,}9426\text{E-12} \cdot \omega^3) \cdot \mu + \\ & + (-7{,}0069\text{E-01} + 8{,}7468\text{E-04} \cdot \omega - 3{,}8480\text{E-07} \cdot \omega^2 + 6{,}1189\text{E-11} \cdot \omega^3) \cdot \mu^2, \end{aligned} \tag{7}$$

where the values of frequency ω have dimension Trad, and the parameter μ concentrations GeO_2 is taken as a mass fraction (percentage divided by 100).

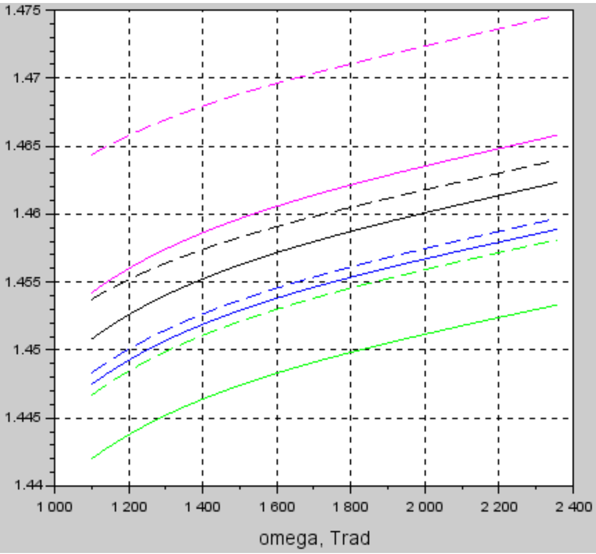

Figure 7 - Dependence of the refractive index on the frequency and content of the GeO2 impurity (the higher the graph, the greater the impurity content: 0%, 3,1%, 3,5%, 4,1%, 5,8%, 7,0%, 7,9%, 13,5%)

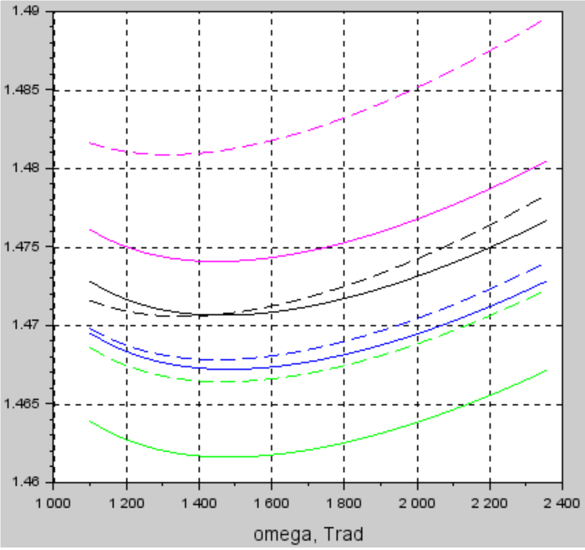

Figure 8 - Dependence of the group refractive index on the frequency and content of the GeO2 impurity (the higher the graph, the greater the impurity content: 0%, 3,1%, 3,5%, 4,1%, 5,8%, 7,0%, 7,9%, 13,5%)

The proposed method of organizing the delay line system is the following: all delay lines have the same length, and the delay step is regulated by alloying additives. Taking into account the orders of magnitude in formula (7), we confine by the linearized dependence of the relative step on the delay increment:

$$\tau = \frac{L}{c} n_{gr}(\omega_0, \mu_0 + \Delta\mu) - \frac{L}{c} n_{gr}(\omega_0, \mu_0) \approx \frac{L}{c} \frac{dn_{gr}(\omega_0, \mu_0)}{d\mu} \Delta\mu, \qquad (8)$$

where ω_0 – fixed frequency; μ_0 – the central value of the concentration of alloying additives; $\Delta\mu$ – a small increase in concentration relative to the central value.

For the specific example, let us set the central value of the concentration 5% ($\mu_0 = 0{,}05$). After differentiating the dependence (7), we obtain the calculated formula:

$$\tau(\omega_0, \mu_0) = (5{,}9912\text{E-}02 + 1{,}0875\text{E-}04 \cdot \omega_0 - 3{,}0856\text{E-}08 \cdot \omega_0^2 + 8{,}0615\text{E-}12 \cdot \omega_0^3) \cdot \Delta\mu . \qquad (9)$$

The results of calculations using formula (9) are given in Table. 2 – 4. Analysis of Table 2 – 4 shows the following. Required step τ delays of 100 fs (10^{-13} s) is ensured at the line length of about 0,3 m by the increment of the concentration GeO2 about 1%. The doping accuracy should be 0,01%.

Table 2 – Delay step values τ for a wavelength of 1530 nm (ω_0=1232 Trad)

$\Delta\mu$	Delay on the length of the lines L, m				
	0,03	0,1	0,3	1,0	3,0
0,01	1,6213E-13	5,4044E-13	1,6213E-12	5,4044E-12	1,6213E-11
0,001	1,6213E-14	5,4044E-14	1,6213E-13	5,4044E-13	1,6213E-12
0,0001	1,6213E-15	5,4044E-15	1,6213E-14	5,4044E-14	1,6213E-13
0,00001	1,6213E-16	5,4044E-16	1,6213E-15	5,4044E-15	1,6213E-14

Table 3 – Delay step values τ for a wavelength of 1570 nm (ω_0=1911 Trad)

Δμ	Delay on the length of the lines *L*, m				
	0,03	0,1	0,3	1,0	3,0
0,01	1,5995E-13	5,3317E-13	1,5995E-12	5,3317E-12	1,5995E-11
0,001	1,5995E-14	5,3317E-14	1,5995E-13	5,3317E-13	1,5995E-12
0,0001	1,5995E-15	5,3317E-15	1,5995E-14	5,3317E-14	1,5995E-13
0,00001	1,5995E-16	5,3317E-16	1,5995E-15	5,3317E-15	1,5995E-14

Table 4 – Delay step values τ for a wavelength of 850 nm (ω_0=3529 Trad)

Δμ	Delay on the length of the lines *L*, m				
	0,03	0,1	0,3	1	3
0,01	2,3725E-13	7,9082E-13	2,3725E-12	7,9082E-12	2,3725E-11
0,001	2,3725E-14	7,9082E-14	2,3725E-13	7,9082E-13	2,3725E-12
0,0001	2,3725E-15	7,9082E-15	2,3725E-14	7,9082E-14	2,3725E-13
0,00001	2,3725E-16	7,9082E-16	2,3725E-15	7,9082E-15	2,3725E-14

Such parameters are quite achievable with the existing technology for the production of FO by deposition from a gaseous mixture. In Tables 2 – 3 are given values for wavelengths differing by 40 nm. In the vicinity of the 1550 nm transparency window, this corresponds to a bandwidth of 4 THz. In this band, 40 frequency channels with a width of 100 GHz are completely stacked according to the G.692 frequency plan [1]. In this case, for the extreme values of the wavelengths, the difference in the delay step does not exceed 2%. Thus, the proposed method provides sufficient broadband in the region of an individual carrier. In broadband systems, it is necessary to use different delay line systems for carriers that are separated by more than 5 – 10 THz.

The conclusion. The proposed models and the performed calculations show the principal possibility of densification of the narrow-band channels of the FOTS by approximately an order of magnitude at the existing level of the technology of manufacturing optical components.

Calculations for parametric models are performed by Starenkiy I.V. and Kostyuk V.V. using free software SciLab.

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