Multichannel fiber sensor for time delay and optical pulse form measuring

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Abstract. This paper presents a description of engineering solutions and physical diagram of a device meant to measure spatially resolved time form of optical signals with detection accuracy up to 0.1 ns and a scalable number of monitoring points. It has been demonstrated that the number of simultaneously detected optical signals within the limit is up to one million. There are no moving mechanical units in the device design. A method for reducing the total length of the optical fiber based on the principle of the cascade optical delay is proposed for the multichannel sensor of diversification. The number of measured signals reaches a million. The capabilities and constraints of the described engineering solution for measuring the pulse form and monitoring the diversification of the multicomponent optical signals have been demonstrated. The principle of calculating a multichannel fiber device for recording optical pulses is presented and shown that the fiber length is up to 15 km for the detection system of 128 optical signals 100 ns long each. Generally, the number of measured signals may reach a million.

1. Introduction
One of the urgent problems of experimental physics is the need to detect the diversification of some fast-flowing phenomena and processes. For example, a pulse shape change in the cross section of a spatially extended laser beam passing through a non-ideal amplifying medium [1] or a medium with radiation frequency conversion [2], as well as the dynamics of multichannel non-ideal shock waves in experiments on object compressibility [3].

The existing detection methods are based on use of matrix photodetectors, such as charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS) matrices [4,5]. Serial equipment implementing such devices allowing achieving a shooting speed of up to one million frames per second. The diversification parameters of luminescence appearing under a nonuniform shock wave are successfully measured using digital streak-camera. This class of equipment is based on image scanning on the surface of the detector due to high-speed rotation of the reflecting surface. Complex design and engineering solutions and expensive components are used.

The shape of the laser pulse is usually monitored using high-speed photodetectors having typical rise time up to tens of picoseconds. However, currently there are no engineering solutions and commercially available equipment that would allow to perform spatially resolved detection of the shape of each pulse in the frequency operation mode, as well as when a multi-component signal is located on the surface of arbitrary shape.

The main purpose of the proposed device is to detect the pulse form, the jitter of a multicomponent optical signal in the duration range from hundreds of picoseconds to microseconds and the
diversification of its components from ns to hundreds of microseconds. The principle of operation of the proposed device is based on the ability to perform multi-channel fiber integration [6] and proportional delay of optical signals. Prospective areas of application: diagnostics of the spatially distributed pulse shape over the cross section of the radiation beam in the pulse-periodic mode, monitoring of the diversification of the signal generation in multicomponent optical signals located on the surface of arbitrary shape.

The purpose of this effort is to formulate technical foundations of a measuring system based on multichannel fiber-optic system with photodiode detection of shape and time delay of multicomponent (10 to several thousand) optical pulses with time interval detection accuracy about 0.1 ns. For this purpose, the following tasks are resolved:

- The principle of design, calibration, scalability of the fiber-optic multi-channel detector of shape and diversification of multicomponent optical signals is elaborated.
- The basic ratios are formulated, allowing to define technical appearance, specifications and constraints of the measuring system based on the fiber-optic multichannel detector of shape and diversification of multi-component optical signals.

2. Detector operation principle

State-of-the-art optical fibers have low radiation leakage in a wide wavelength range from 0.4 dB to 0.2 dB per 1 km. The current urgent task of monitoring the signal diversification of the multichannel optical system can also be resolved using fiber-optical technologies and techniques. The current level of technology allows to create prototypes with the number of combined signals up to 128 [7,8]. The typical distance that laser radiation currently travels using single-mode radiation is tens and hundreds of kilometers. The distance is constrained due to the fact that when the length of the fiber at the given laser power increases, a moment inevitably comes when various nonlinear effects occur, for example, forced combination scattering, described in more detail in [9,10].

State-of-the-art semiconductor photodetectors have high sensitivity and allow to detect radiation with power up to -35 dB, which allows to detect single photons using power amplifiers [11,12]. Now consider the design diagram of the device, which is capable of detecting the signal shape of multichannel optical system (see Figure 1). The device principle of operation is as follows:

- The multichannel system of inputting optical fiber apertures (POS. 1.1...1.4 in Figure 1) with the set geometrical parameters is separately generated, the quantity of detection channels is determined based on the general requirements to the investigated process and extreme capabilities of the measuring equipment (possible scaling of the measuring system within the specifications of the fiber-optic system, photodetector and oscilloscope).
- The signals of the multichannel system arrive at the input of optical fibers in a systematized/accounted for sequence, for which the fibers are labelled.
- The output connectors of optical fibers by means of multi-fiber cables (POS. 2.1..2.4 in Figure 1) are connected to multichannel fiber switch (3.1..3.4 in Figure 1), where each signal passes an optical path with an equidistant increase in the length of the optical fiber in the coils (POS. 2.1..2.5 in Figure 2) according to the channel serial number. For the diagram of the multichannel fiber switch, see Figure 2.
- The optical paths in the switch are configured and aligned with the sequence of connectors on the front panel during installation and adjustment by changing the fiber length according to the Equation (1).

\[ L_{f_{nc}} = L_b + (N_c - 1) \times L_t, \]  

(1)

where \( L_{f_{nc}} \) is length of optical fiber for channel, \( L_b \) is length of basic channel (the first channel) of the switch, \( N_c \) is number of channel, \( L_t = C \times t/n \) is length of fiber determined due
to necessary of time delay between channels (t is estimated difference, n is refractive index of optical fiber).

**Figure 1.** Diagram of four-channel fiber diversification detector. 1.1 to 1.4 – system of optical fiber apertures with set geometrical parameters, 2.1 to 2.4 – multi-core cable of the same length (multi-mode/single-mode depending on the intensity of the object's glow), 3.1 to 3.4 – multichannel fiber switch, 4.1 to 4.4 – transport fiber (multi-mode/single-mode as required), 5.1 to 5.4 – photodetector, 6.1 to 6.4 – coaxial cable, 7 – oscilloscope, 8 – fiber-optic divider, 9 – reference measurement point.

**Figure 2.** Diagram of multi-channel fiber-optic switch (MFS). 1 – front panel with input connectors, 2.1 to 2.5 – coils with equidistant optical fibers (multi-mode/single-mode as needed), 3.1 to 3.6 – fiber optic combiner, 4 – panel with output connector.
• After a temporary channel switching, signals are combined in the fiber-optic combiners (POS. 3.1...3.5 in Figure 2) and sent via one optical fiber to the photodetector (POS. 5.1..5.4 in Figure 1). Multi-stage integration is possible, see Figure 2, or simultaneous integration in the multi-channel device).

• The photodetector generates an electrical signal, which is sent via the coaxial cable (POS. 6.1..6.4 in Figure 1) to the oscilloscope (POS. 7 in Figure 1). It is possible to place the photodetector within the switch, which will reduce the number of detachable connections, and place the connector at the switch output for connecting the coaxial cable from the oscilloscope, which in both cases detects the combined shape of the signal sequence, see Figure 3.

![Figure 3](image)

**Figure 3.** Expected shape of combined signal detected by oscilloscope. N1 to N4 – numbers of detection channels, L1 to L8 – numbers of lines of optical fibers in channel dt2 to dt8 – time jitter of measured signals relative to reference one.

The principle of high-precision measurement of pulse diversification and shape of multiple optical signal is that the design of fiber-optic coils from the structure of the MFS sets the detected pulse period with precision to determine the length of the optical fibers in the coils. The error in determining the length of the optical fiber is currently up to 0.1 m when using measurement line up to several kilometers. Thus, the error in generating the detected signal period in one channel is be no more than 1 ns. The first fiber-optic line for each channel is the reference one for the subsequent lines in the channel and detects the optical signal from the reference radiation source. It can be either a special master oscillator or one of the measured points taken as a reference (see POS. 9 Figure 1). It can also be the central point of the measured laser beam. The radiation from the reference point to the measurement channels is distributed using fiber-optic splitters (POS. 8 in Figure 1) that has a similar design with the fiber optic combiners. Due to the proposed engineering solution, the measurement process gives the opportunity of:

• performing a simple setting of zero reference time relative to the investigated process;
• calculating also the position of each pulse relative to the pulse period;
• combining the measured pulses in time with an accuracy of 0.1 ns a to compare the shapes and for statistical processing of a set of pulses;
• scaling the measurement system using multi-channel detection systems existing on the market of oscilloscopes;
• performing a simple calibration of the fiber system regarding errors of determining diversification by: simultaneous input of the same signal to all fibers input (performed before the final installation of the input apertures) and the detected waveform (the error in determining the position of the received pulses will not be greater than the instrument error).

3. Extreme capabilities of device
Define the potential capabilities and functional constraints of the device based on typical fiber-optic components and a standard semiconductor detector. The difference of occurrence time $d_{tN}$ (jitter) of $N$-th pulse is defined as follows, Equation (2).

$$d_{tN} = t_{N} - T \times (N - 1) - t_0,$$

(2)

where $t_N$ is countdown of the $n$-th pulse on general scale, $T$ is pulse period (determined by the design), $N$ is number of signal fiber in multichannel switch, $t_0$ is countdown of reference pulse arrival at general scale.

In this case, the maximum possible number of detection channels is determined by the availability of the necessary equipment. The required diversification measurement accuracy determines the class of oscilloscopes used (at the level of units of GHz and above) and high-speed photodetectors (with the leading-edge rise time at the nanosecond scale). Such oscilloscopes have a recording depth of up to ms in the four-channel operation mode, thus, taking into account the pulse period of $1 \mu$s (the case with a microsecond jitter) such oscilloscope is capable of detecting up to a hundred signals at once, and up to a thousand at pulse period of $100 \text{ ns}$(the case with a nanosecond jitter). This makes it possible to apply the following engineering solution: several measurement channels are submitted after the switches to the intermediate switch and then simultaneously input to one photodetector, and then the combined electric signal is detected by the oscilloscope. Such a solution will ensure the scalability of the measuring instrument circuit and allow more efficient use of high-speed oscilloscopes. The limit number of detected signals $N_s$, for a specific measurement circuit can be calculated as follows, Equation (3).

$$N_s = \frac{T_i}{T} \geq N_k \times (N_l - 1) \times N_{ap},$$

(3)

where $N_k$ is number of oscilloscope channels, $N_l$ is number of the optical fibers in input multicomponent aperture of channel, $Ti$ is depth of oscilloscope recording, $T$ is pulse period, $N_{ap}$ is scale multiplier.

So, the existing constraints are associated with the oscilloscope specifications, as well as with the maximum permissible amount of optical fibers, which today's components allow to use for the design of measuring systems with the permissible leakage.

The second constraint of functionality is related to the fact that when the number of detected signals increases, the length of fibers and the number of coils in the fiber-optic multichannel switch increases as well. This can be estimated as follows: the length of each channel in the switch is determined by Equation (1) and in the limit for 128 channels per one coupler (modern single-mode fiber couplers) reaches a length of 12,000 m for 128 channels, and the total length of the serial addition will be about 840 kilometers of optical fiber. Cascade mounting of the couplers will reduce the total length of the optical fiber and simplify the mounting of the measuring system. For the principle diagram of cascade mounting of several $n \times 1$ couplers, see Figure 4. A similar diagram with use of an 8-channel input coupler and 16 cascades allows to reduce the total length of the fiber up to 15 km for the detection system of 128 optical signals.

Cascade assembly can be carried out up to splitting of optical fibers into pairs. In this case, there is an issue of the optimal number of couplers for combining channels, in fact each of the channels shown in Figure 4 can be divided to the limit by the couplers, but the leakage on fiber-optic welds will
increase, which will result in a proportional increase in losses and reduce the amplitude of the signals in the channels with an increase in the number of couplers, and will also lead to an increased number of mounting operations. In principle, 1 km of optical fiber (at a wavelength of 1.55 µm, leakage is 0.25 dB/km) is proportional to five fiber welds (approximately 0.05 dB per weld). This means that this factor shall be taken into account in the design of the measurement system when estimating the optical loss budget and the design optimization. The total length of the optical fiber of the measuring system multi-cascade channel can be calculated using the following Equation (4).

\[
L = M \sum_{i=1}^{N/M} (L_{b} + (i - 1) \times L_{f_{Nc}}) + \sum_{i=1}^{M} L_{f_{SNc}},
\]

where \(L_{b}\) is length of reference optical fiber, \(L_{f_{Nc}}\) is length of largest channel in cascade (calculated as per Equation (1)), \(M\) is number of cascades, \(L_{f_{SNc}}\) is total length of optical fiber in cascade.

![Figure 4. Assembly diagram of four-cascade multichannel coupler. K1 to K4 – cascades of the input apertures, MFS1 to MFS4 – multi-channel fiber switches.](image)

4. Conclusion

The paper presents the results of elaboration of the technical appearance of the multi-channel fiber diversification detector. It has been demonstrated that the maximum number of detection channels is limited by the recording depth of used oscilloscope, the quality and quantity of the available equipment. The number of measured signals in the limit reaches a million. The capabilities and constraints of the new engineering solution for measuring the pulse shape and monitoring the diversification of the multicomponent optical signals have been demonstrated. The main advantages of the proposed principle and the device for measuring diversification and time intervals are: lack of mechanical moving parts and discrete optical elements, high repairability, operation at a considerable distance from the investigated object, noise immunity, simple synchronization with the investigated object, possibility of direct application in hydrodynamic experiments, wide spectral range of signals, automatic signal processing, simple calibration and high accuracy of timing data measurement, low cost of components, possibility of building entirely on domestic components.

In many cases, associated with the creation of high-quality laser emitters, there is a need for a rapid diagnosis of the laser pulse time shape using the beam section for pulse-periodic operation mode. The main technical result of the implementing such equipment will be the capability of monitoring the pulse shape along the beam cross section during each pulse in the frequency operation mode of the investigated device. As a result, this will qualitatively improve the efficiency of work in the area of laser physics and technology in general for enterprises of the domestic laser industry.
The engineering solutions presented in this paper will significantly improve the efficiency of research and development aimed at designing new instruments and methods of experimental physics.

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