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OPTOPHYSICAL MEASUREMENTS

MINIATURE IMAGE-CONVERTER CAMERAS FOR MEASUREMENT OF THE TEMPORAL CHARACTERISTICS OF OPTICAL PULSES IN NANO- AND PICOSECOND RANGES

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The task of studying the temporal structure of optical pulses in the nano- and picosecond ranges, and measurements of the temporal characteristics of the pulses, was undertaken. In order to resolve this task, measurement instruments for the temporal characteristics of optical pulses were created: miniature image-converter streak cameras with picosecond temporal resolution. The functional capabilities and examples of use of the specified cameras are described. Their principle of operation, design, characteristics, and functions are examined. The manufacturing process of the time-analysis image-converter streak tubes for these cameras, performed in a unique high-vacuum manufacturing site, is described. The functional capabilities of the software to control the image acquisition process, as well as for processing and analysis of the images captured by the image-converter streak cameras, are studied. The metrological and chief technical characteristics of the miniature image-converter streak cameras are presented. With the use of the miniature picosecond image-converter streak camera, the temporal structure of the radiation of a semi-conductor pulsed laser was studied, the pulse form was determined and their duration was measured, with an estimation of the measurement error. It is shown that miniature picosecond image-converter streak cameras are an effective instrument for controlling the parameters of the radiation of nano- and picosecond pulsed lasers in the course of their development, adjustment, tests, and application. Information on the actual temporal form of the laser pulses, obtained by the image-converter streak cameras, is of great value for developers of pulsed lasers, as well as for specialists in the fields of laser distance measurement and spectroscopy.
Keywords: *image-converter streak camera, image-converter streak tube, pulsed laser, pulse duration, measurement instrument, laser radiation metrology.*

Introduction. High-speed metrological equipment is widely used in various areas of science and technology to monitor the temporal characteristics of optical pulses [1, 2]. In particular, in order to enhance the precision of distance measurement, it is necessary to reduce the duration in a pulsed laser of a sounding laser pulse [3]. The use for this purpose of picosecond pulsed lasers, radiating pulses of duration 10^{-12}–10^{-9} s, evoke the necessity for measurement instruments of the temporal characteristics of single optical pulses within the specified time span.

The dynamic characteristics of optical pulses are usually measured by a device consisting of an oscillograph and a high-speed photo diode. The pass-band of existing oscillographs reaches 110 GHz (Infiniium UXR-Series Oscilloscopes, https://www.keysight.com/ru/ru/assets/7018-06242/data-sheets/5992-3132.pdf), which corresponds to a temporal resolution of 4 ps. However, the temporal resolution of a measurement system will be greater, since the best samples of semi-conductor photo diodes for the visible range have a pass-band on the order of 40–50 GHz (2021 Optoelectronics & Photonics – MACOM, https://www.macom.com/files/live/sites/ma/files/pdf/2021%200pto_031021_r21_final_lr.pdf). Stroboscopic oscillographs, the

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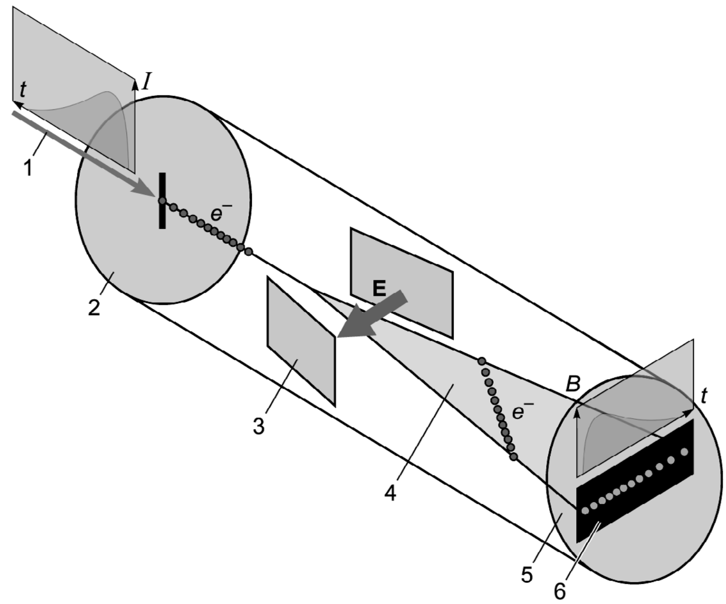

Fig. 1. Operating principle of an image-converter streak camera: *1*) input optical signal; *2*) photocathode; *3*) capacitor type deflection system; *4*) electron beam; *5*) phosphor screen; *6*) image of the sweep trace of an optical signal; *I* – input radiation intensity; *B* – phosphor screen brightness; *t* – time; e^- – photoelectrons; **E** – deflecting pulsed electric field.

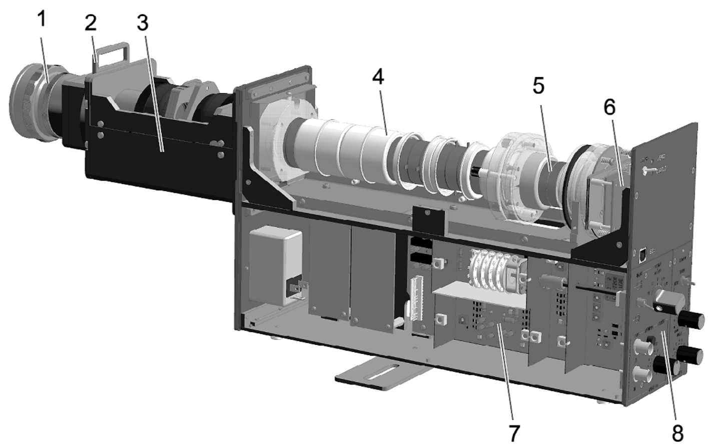

Fig. 2. Main structural elements of the K016 image-converter streak camera: *1*) input objective; *2*) removable input slit; *3*) input optics unit, including the pair of objectives of the inverting system and the set of neutral density filters between them; *4*) PV-207 image-converter analyzer; *5*) electron-optical luminosity amplifier; *6*) semiconductor matrix photoelectric detector; *7*) power and control electronics units; *8*) elements of ICSC control.

effective pass-band of which can exceed 100 GHz, can be used only for a repeating pulse signal. An alternative is the use of photochronographic image-converter streak cameras (ICSC) [4], suitable for studying single signals and having temporal resolution up to 0.1 ps [5–7].

Figure 1 illustrates the principle of operation of a photochronographic ICSC. Optical radiation *1* of intensity *I*, passing through an input slit to the photocathode *2* of the image-converter streak tube (ICST), is transformed into a stream of photoelectrons. This stream is deflected (deployed) by the pulsed electric field **E** in a perpendicular slot of the direction and impinges on the luminescent screen *5* placed on a fiber-optical plate (FOP), where it is transformed to a light stream. The image *6* of the input slit, deployed on the ICST luminescent screen, the brightness *B* of which is proportional to the instantaneous radiation power, is recorded by means of a semi-conductor matrix photodetector (not shown in Fig. 1). From this image, it is possible to determine the form of the optical pulses and measure their temporal characteristics.

The purpose of the real research – the description of functionality created in VNIIOFI the miniature ICSC, allowing to investigate temporal structure of optical pulses with picosecond temporal resolution, and experience of their application for measurement temporal harakgeri-stiklazerny impulses in nano- and picosecond ranges.

The K016 ICSC device. The K016 ICSC is developed and produced at VNIIOFI based on the ICST specialized time-analyzer [8]. An ICSC is a miniature monoblock construction, and Fig. 2 shows its basic elements (with the external casing panels and the electromagnetic screens removed). The input optical unit *3* includes a pair of lenses of the turning system and a set of neutral optical filters between them. The ICSC casing contains the ICST time-analyzer *4* with the photocathode, a beam deflector and the luminescent screen on an FOP, an image-intensifier tube *5* with an FOP at input and output, and a counting device based on a semi-conductor matrix photodetector *6* from an FOP at input. An FOP makes it possible to transfer the image of the process under study through an optical contact between the time-analyzing ICST, a brightness amplifier, and a matrix photodetector. Exclusion of the intermediate lenses makes it possible to minimize light loss, and significantly reduce the overall dimensions of the ICSC. A modern element base is used in the power and electronics-control units *7*.

The image of the scan of an optical signal is recorded by a counting device based on a semi-conductor matrix photodetector with fiber-optic input (RU-07 Wide-Format CCD Counting Device with Fiber-Optic Input and a USB Interface, https://bifocompany.com/rus/p-rs-ru07.php.htm). In order to increase the brightness of the image, an image-intensifier tube with a microchannel plate, jointed by fiber optics with the time-analyzing ICST and the counting device, is additionally installed in the K016 camera.

Manufacture and assembly of the time-analyzing ICST. A PV-207 time-analyzing ICST was developed for the K016 camera, which is the upgraded ceramic-metal version of the PV-206 ICST (https://bifocompany.com/rus/p-tub-pv206.php.htm). The PV-207 ICST has a photocathode on uviol glass, an accelerating network electrode near the photocathode, a focusing electrode, a deflecting system with two pairs of plates that deflect the electron beam to mutually perpendicular directions, and a luminescent screen on FOP.

The PV-207 ICST is produced at VNIIOFI in a unique high-vacuum manufacturing system (https://www.VNIIOFI.ru/news-list/pervyj-v-rossii.html). The system makes it possible to study the properties of photoemitters, current emission amplifiers, electronic and sense matrices and other components of vacuum photoelectronic devices, and manufacture these components. With this, it is possible to manufacture and collect high-speed ICSTs with subpicosecond temporal resolution. Figure 3 schematically shows the technological complex with a place of the operator (it is located behind a complex). The technological complex consists of several high-vacuum chambers *4* and *7–9,* vacuum manipulators *3*, cold hydrostatic test system *5* in high-vacuum volume, and also the control system of technological process mounted in a separate rack *10*. High-vacuum chambers have multistage systems of pumping and are connected consistently through vacuum locks *6*.

The fabrication process of manufacturing and assembly of an ICST occurs as follows. A substrate of the photocathode is placed in the container and is soldered onto an exhaust unit in which, separately from the rest of the structural element of the ICST, a photocathode is prepared and its quality is estimated. Then the structural element of the ICST without the photocathode is placed in the process system in a special attachment located in the cold hydrostatic test chamber *4*. The container with the photocathode is placed in the vacuum chamber *9*. After the warming and pumping out of the entire system, the container with the photocathode is moved to the vacuum chamber *8,* where it is opened by means of the vacuum manipulator *3*. After the container is opened, the substrate with the photocathode is moved to the cold hydrostatic test chamber, established opposite the ICST structural component, and pressed into a special place of this component. The operator administers and monitors this technological process through the control stand *10*.

Software. The image recorded by a multi-element photodetector over the USB interface is entered into a computer with the Fast Glance software. The chief functions of Fast Glance are display representation and processing of images taken by the ICSC, as well as measurement of the temporal characteristics of optical pulses according to GOST R ISO 11554-2008, "Lasers and laser installations (systems). Test methods for lasers and measurements of power, energy, and temporal characteristics of a laser beam" (ISO 11554:2006, "Optics and photonics – lasers and laser-related equipment – Test methods for laser beam power, energy and temporal characteristics"). The Fast Glance program corrects the geometrical and photometric distortions of the image that occur in the electron-optical path of the camera. Photo capture with accumulation and averaging is supported, and here programmatic correction of jitter is possible. It is also possible to perform arithmetic operations with the images, define

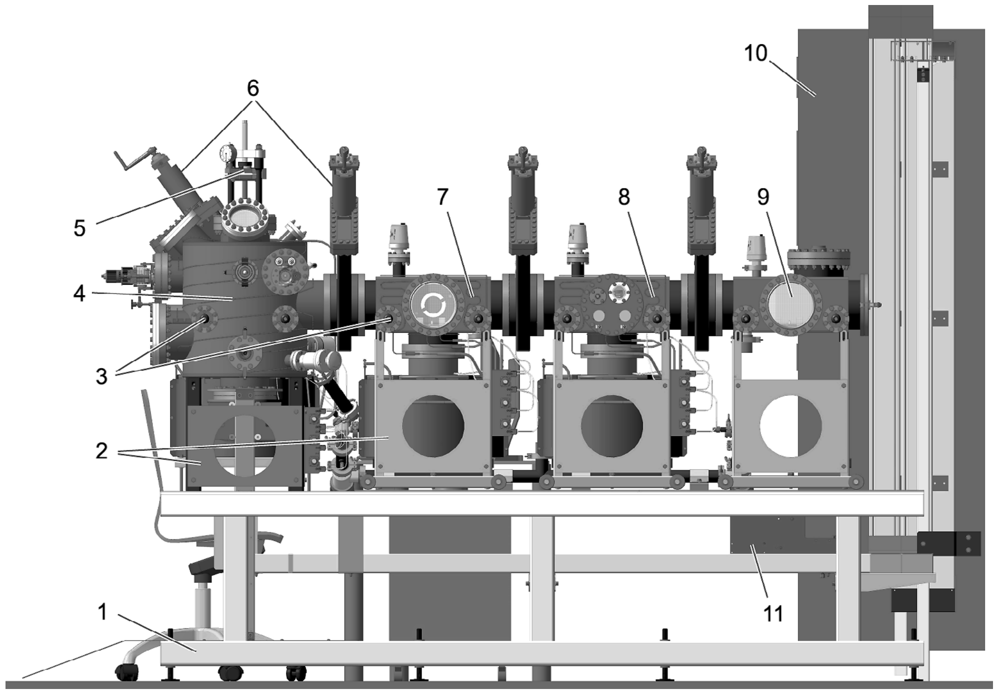

Fig. 3. Ultrahigh vacuum processing system with control rack and operator work station: *1*) frame; *2*) adjustable supports; *3*) vacuum manipulators; *4*) cold hydrostatic test chamber; *5*) cold hydrostatic test system; *6*) vacuum seals; *7–9*) chambers for transfer, opening, and loading, respectively; *10*) control rack; *11*) pneumatic supply system.

various numerical characteristics of the image, construct luminosity profiles along the spatial and temporal axes and measure the intervals between cursors, and measure the temporal characteristics of one or several pulses. Images on the computer display can be presented in several options of pseudo-coloring, which increases the number of visually distinguishable brightness levels. The image export function to the TIFF graphics format makes it possible to apply other means of image processing if necessary.

Characteristics of the K016 ICSC. The K016 ICSC passed tests for the purpose of confirming the type of measurement instrument (registration No. 71686-18), and is registered as a measurement instrument for temporal characteristics of optical pulses [9].

Main technical characteristics of the K016 ICSC

Maximum frequency of triggering the camera	≥8 Hz
Dimensions* (H × W × L), mm	≤(225 × 115 × 610) mm
Mass	≤10 kg
Network supply voltage with frequency 50–60 Hz	85–264 V
Power consumption from the network	≤35 W
Service conditions:	
environmental air temperature	15–35°C
relative humidity of air	≤80%
atmospheric pressure	94–106 kPa

* Specified without accounting for an input lens.

More detailed technical characteristics of the ICSC are presented on the web page (https://bifocompany.com/rus/p-cam-K016.php.htm).

The K016 ICSC has picosecond temporal resolution, and is capable of revealing the fine temporal structure of a laser pulse. This structure cannot be found with oscillograph measurements because of the insufficient pass-band width of the oscillograph or photo diode, used to transform an optical signal into an electric one [10]. Table 1 presents the metrological characteristics of the K016 ICSC.

TABLE 1. Metrological Characteristics of the K016 ICSC

Characteristic	Sweep range, ns/cm				
	0.1	0.3	1.0	3.0	10.0
Limit of measurement of time intervals, ns, at least	0.16	0.50	1.70	5.00	18.00
Temporal resolution at width of opening 50 μm at wavelength 532 nm, ps, no greater than	5	7	17	50	150
Limit of the chief measurement error of time intervals with their duration at least two temporal resolutions on the corresponding range of sweep trace, %	±15				
Region of spectral sensitivity, nm	400–800				

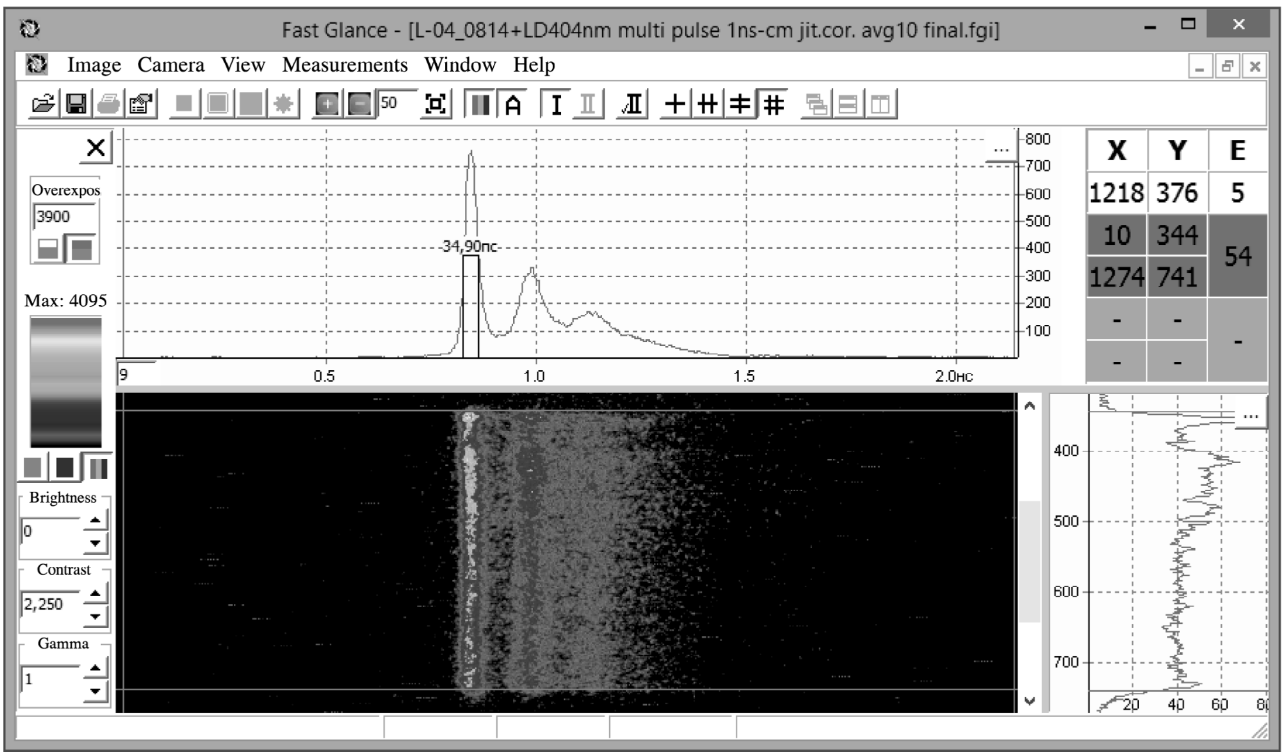

Fig. 4. Work window of Fast Glance software, showing the image of a pulse of the L-04 picosecond semiconductor laser, recorded by the K016 image-converter streak camera, and the pulse form obtained as a result of image analysis; the sweep range and sweep duration of the ICSC are 1 ns/cm and 2.12 ns, respectively.

Application of the K016 ICSC to measure the temporal characteristics of laser pulses. In order to illustrate the capabilities of the K016 ICSC, Fig. 4 shows the form, recorded with this type of camera, of a pulse of the L-04 picosecond semi-conductor laser radiator (https://bifocompany.com/rus/p-light-L04.php.htm), operating in amplification modulation mode (gain switching). The pulse duration at a level of 0.5 times the maximum of the intensity, measured according to GOST R ISO 11554-2008 (ISO 11554:2006), is 34.9 ps. The normalized limit of measurement error is ±15% (see Tables 1 and 2). Hence, the result of the measurement of pulse duration in this example is 35 ± 5 ps. The measured pulse duration at a level of 0.1 times the maximum of the intensity is 420 ps.

Publications [10, 11] are devoted to the use of the K016 ICSC measure the temporal parameters of the radiation pulses of nano- and picosecond solid-state lasers.

Conclusion. The characteristics of the K016 ICSC that were studied, and examples of its application, make it possible to draw the conclusion that similar miniature picosecond ICSCs are an effective tool to control the parameters of the radiation of nano- and picosecond pulsed lasers in the course of their development, adjustment, tests, and application. These ICSCs can be used to control the mode of radiation of the laser (single or multipulse), as well as to measure the parameters of laser pulses (duration, time interval between impulses, and ratios of the intensity of pulses in the train of pulses).

In addition, in pulsed laser spectroscopy, a significant effect on the result is rendered by supershort peaks in laser pulses, which can results in undesirable effects as a consequence of the considerable increase in the energy density of laser pulses. Hence, information on the actual form of the laser pulses, obtained by the ICSC, is important not only in the development but also use of nano- and picosecond lasers.

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