Development of the Standard for Laser Pulse Duration in the Picosecond Range

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ABSTRACT

The setup under development is intended to serve as the Russian National Primary Special Standard for Laser Pulse Duration in the range from 10 to 1000 ps. The core components of the standard are a streak camera with picosecond temporal resolution and a Fabry-Pérot etalon illuminated by femtosecond laser pulses. The etalon defines a time interval which is used to calibrate the temporal scale of the streak camera. The standard includes a picosecond laser pulse generator for reproduction and transfer of the unit of laser pulse duration to another measuring instrument or secondary standard. Described are the principles of operation, the construction of the standard, and the results of preliminary experiments to determine its metrological properties.

Keywords: optical metrology, calibration, standard, picosecond laser, pulse duration measurement

1. INTRODUCTION

1.1 Laser Pulse Duration Measurement in the Picosecond Range

Among the temporal parameters of a laser pulse the most important one is certainly its duration. As the shape of the pulse can vary, the strict definition of the term “pulse duration” must be given. The pulse duration is defined by ISO 11554:2006(1) as full width at half maximum (FWHM) of the pulse.

A number of approaches to measure laser pulse duration have been developed up to now. They subdivide into direct and indirect methods of measurement. Direct measurement relies on direct recording of temporal dependence of instantaneous optical power. Measuring instruments utilising the direct method include a photodetector connected to an oscilloscope, and a streak camera. Indirect method implies deriving the information about temporal characteristics of a pulse from other measurable quantities. Such methods include intensity autocorrelation, SPIDER(2), FROG(3), and various modifications of them. Most of them suffer from ambiguities of different kinds, thus the use of the direct method of measurement would always be preferable over the indirect one.

Due to the widespread use of picosecond lasers emitting pulses in the nano- and picosecond range, the need for measuring instruments for temporal parameters of single optical pulses in the above-mentioned range is very high. Typically a high-speed photodetector connected to a fast oscilloscope is used for direct optical pulse duration measurements in the nanosecond range. In order to be able to measure picosecond pulses, such system must have very short rise time. There are ultra wide bandwidth oscilloscopes which have rise time as low as 4.5 ps(4), but in that case the limiting factor is the photodetector rise time, which still don’t exceed 9 ps for the best known examples(5). The use of sampling oscilloscopes is possible only for repetitive signals with well reproducible shape. On the other hand, indirect methods of measurement are intended mainly for femtosecond pulses and their application to picosecond pulses faces many difficulties.

A promising way is to use a streak camera for laser pulse duration measurement. A streak camera can have temporal resolution of about a fraction of picosecond(6). Until recently streak cameras were used mainly as means of observation of the temporal shape of optical signals due to the high uncertainty of measurements. The technological improvements over last decades changed the situation, and now the use of a streak camera as a measuring instrument seems to be a reasonable solution.

1.2 Standard for Laser Pulse Duration

From the metrological point of view, all measuring instruments for some physical quantity must have metrological traceability to the measurement standard of the unit of that quantity. Traceability is usually obtained by calibration of a measuring instrument against the standard. If no standards exist for some physical quantity then no measuring instruments with metrological traceability are available.

Existing Russian National Primary Special Standard for the Units of Energy, Energy Density Distribution, Pulse Duration, and Wavelength of Laser Radiation (GET 187-2010)(7, 8) reproduces the unit of laser pulse duration in the range from 1 μs down to 1 ns, so it can’t be used in the picosecond range. The cause limiting its lowest measurable duration

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value is the rise time of the photodetector used in the standard to measure pulse duration. Thus a new standard based on other principle is required to be developed in order to extend the range of laser pulse duration that can be measured with metrological traceability by measuring instruments calibrated against this new standard. For this reason a streak camera with temporal resolution of about 2 ps(9) was chosen as a measuring instrument for the new standard for laser pulse duration.

A standard for laser pulse duration is the setup that assures stable reproduction of the laser pulse of known duration. This pulse duration value is the unit of laser pulse duration reproduced by the standard. The standard must include a sufficiently stable source of picosecond laser pulses, and a measuring instrument for pulse duration measurement. The equipment for calibration of temporal scale of this measuring instrument independently from other standards also has to be included. The setup must also allow transfer of the unit to another measuring instrument for laser pulse duration or a secondary standard.

2. CONSTRUCTION OF THE STANDARD

The setup has two switchable configurations: one for calibration of the standard and the other for reproduction and transfer of the unit of laser pulse duration.

2.1 Calibration of the Standard

2.1.1 Calibration Method

The calibration method is based on the known effect of multiplication of a short optical pulse passing through a Fabry-Pérot etalon due to multiple reflections from its mirrors. If a single sufficiently short pulse is directed to the etalon then the output will be a train of pulses with decreasing intensity, equally separated in time. The time interval between the pulses T is determined solely by the doubled optical path through the etalon: $T = 2nd/c$, where n is the index of refraction of the medium between the mirrors of the etalon, d is the distance between the mirrors, and c is the speed of light in vacuum.

In the present setup a single femtosecond pulse reaching an air-spaced etalon produces a train of femtosecond pulses separated by equal time intervals defined by the thickness of the spacer ring between the mirrors of the etalon. These pulses serve as the temporal markers for calibration of the temporal sweep of a streak camera. The calibration maps the time scale to the sweep coordinate scale on the streak images, producing a sweep calibration function $t(x)$, where t is the time since the beginning of the sweep, x is the coordinate on the sweep.

2.1.2 Calibration Setup

Optical scheme of the setup for calibration of the standard is shown in Figure 1. An Ytterbium femtosecond laser TEMA-150 by Avesta Ltd. generates pulses with 100 fs duration and 70 MHz repetition rate at 1050 nm wavelength.

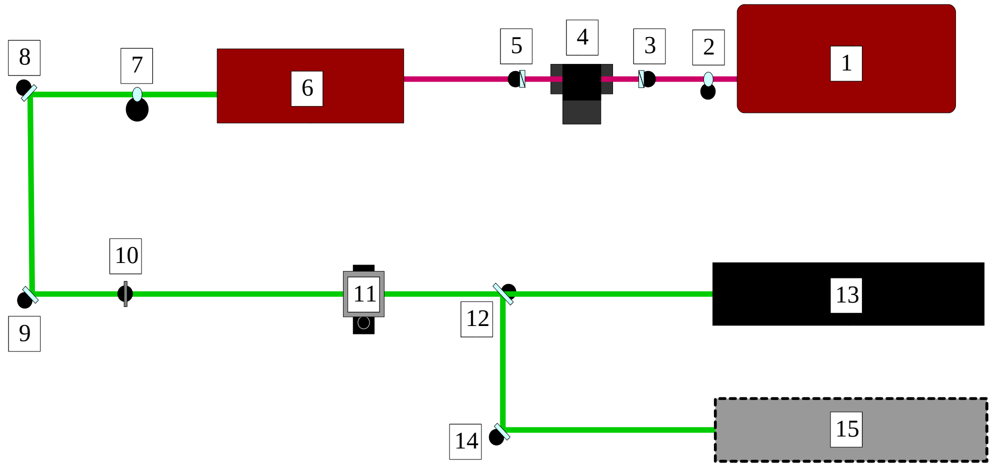

Figure 1. Optical scheme of the setup for calibration of the standard of laser pulse duration. Legend: 1 – Ytterbium femtosecond laser; 2,7 – periscopes for optical axis height matching; 3,5 – polarisers (Glan–Taylor prisms); 4 – electro-optical pulse picker; 6 – second harmonic generator; 8,9,14 – dielectric mirrors; 10 – neutral density filter; 11 – Fabry-Pérot etalon; 12 – 50:50 beam splitter; 13 – streak camera; 15 – another measuring instrument for laser pulse duration.

An electro-optical pulse picker device OG8-1-1 based on the Pockels cell picks out a single femtosecond pulse which then passes through the LBO crystal based second harmonic generator ASG-1050. The output of the laser system described above is a single femtosecond pulse at 525 nm wavelength.

This single pulse is directed to the Fabry-Pérot etalon. A pulse train coming from the etalon is captured by a streak camera. The thickness of the spacer ring of the etalon is chosen so that the time interval it defines would be about 15 times less than the duration of the sweep of the streak camera. The streak camera is triggered by the synchronisation signal coming from the pulse picker control unit. Additionally a beam splitter is installed along the optical path after the etalon, that enables the use of the same setup for calibration of another measuring instrument or a secondary standard. In order to maintain intensity of the input beam within the streak camera dynamic range, neutral density filters are installed before the streak camera.

2.1.3 Measurements and Data Processing

Summing up the image of the pulse train captured by the streak camera across the sweep direction yields a few peaks of decreasing height corresponding to the pulses of the train from the etalon. The position of every pulse x_i is calculated using the centre-of-gravity technique. At the centre points of the intervals between the peaks with coordinates $c_i = (x_i + x_{i+1})/2$, the values of the sweep coefficient $k_i = T/(x_{i+1} - x_i)$ are computed, where T is the temporal interval defined by the etalon, x_i and x_{i+1} are the positions of two consecutive peaks. The resulting data set $\{(c_i, k_i)\}$ is fitted by a polynomial function $k(x)$ using the least squares method. The thorough determination of the $k(x)$ is achieved by capturing multiple images of the pulse train at the different positions on the sweep. The position of the pulse train on the sweep is adjusted by varying the delay of the streak camera triggering signal. The data sets $\{(c_i, k_i)\}$ from many images are combined together. The sweep calibration function $t(x)$ is derived from $k(x)$ by integration: $t(x) = \int k(x)dx$.

The sweep calibration function is used to transform the streak images in order to eliminate the sweep nonlinearity. Correction of sweep nonlinearity allows also the use of a simple formula for pulse duration measurement. In this case $k(x)$ becomes constant k_0 = mean $k(x)$, and the pulse duration τ will be just a product of its value Δx in pixels on sweep coordinate scale, by k_0: $\tau = k_0 \cdot \Delta x$.

The function $k(x)$ before and after the sweep nonlinearity correction as well as the experimental points $\{(c_i, k_i)\}$ are shown in Figure 2.

The calibration procedure also includes determination of the instrument function width of the streak camera. The instrument function is by definition a response of an instrument to an infinitely short input pulse. Since the femtosecond pulses used for calibration of the temporal sweep of the streak camera are much shorter than its temporal resolution, then the pulses observed on the streak images are essentially the replicas of the streak camera instrument function. The measured width of the instrument function is used later to correct the systematic error associated with it.

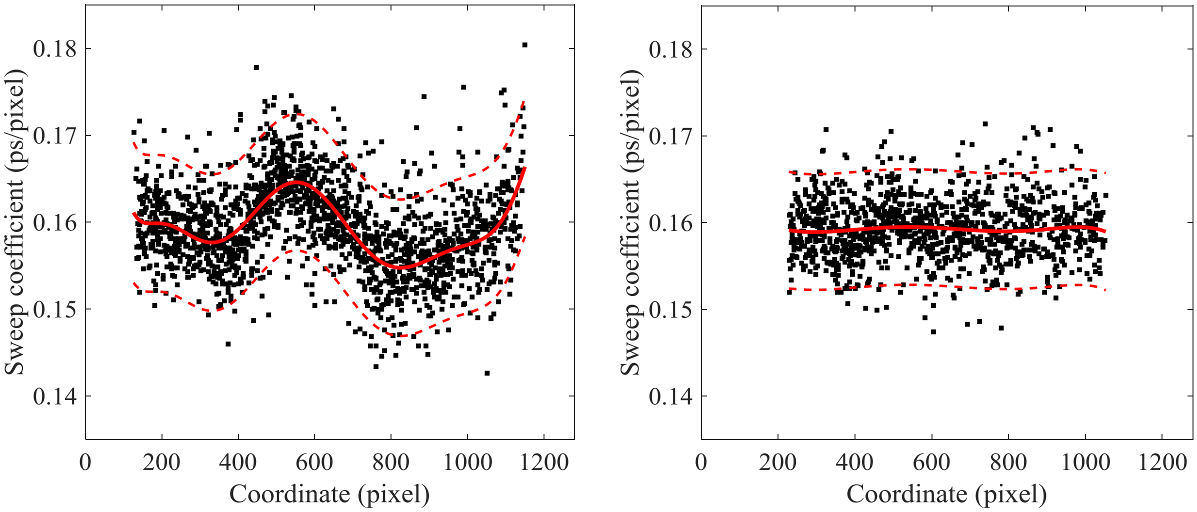

Figure 2. Plot of sweep coefficient versus sweep coordinate on the sweep before (a) and after (b) sweep nonlinearity correction. The dashed lines show borders of 95% confidence interval for the sweep coefficient at given coordinate.

2.1.4 Calibration Uncertainty

In addition to the fit of the experimental data the least squares method gives also the standard uncertainties $u_k(x)$ of the fitting function values. The maximum value of standard uncertainty of the fit, max $u_k(x)$ represents a type A standard uncertainty of the calibration – u_A.

The other sources of uncertainty of the calibration are associated with the temporal interval defined by the etalon. Namely the measurement uncertainty of the thickness of the spacer ring between the mirrors of the etalon, thermal variation of that thickness, and the uncertainty of refraction index of air due to variations in environmental conditions in the laboratory. All these factors contribute to a type B standard uncertainty of the calibration – u_B.

Calculations based on the properties of the constituent parts of the standard and its operating conditions demonstrated that u_B is much less than u_A, so the combined standard uncertainty of the calibration u_c is almost equal to its type A component, $u_c \approx u_A$.

Results of preliminary experiments in calibration of the standard suggest the value of u_c to be about 2% for the fastest sweep of the streak camera.

2.2 Reproduction of the Unit

2.2.1 The Setup

For the standard to reproduce a laser pulse in the picosecond range, a picosecond laser has to be included in the setup. However during the development of the standard it was decided to use a fibre-optical stretcher instead. Fibre-optical stretcher here is a device that stretches a pulse coming from the femtosecond laser used for calibration of the standard so that the pulse duration falls into the picosecond range. Particular pulse duration value is determined by the fibre dispersion, and is proportional to the fibre length. The optical scheme of the setup in this configuration is shown in Figure 3. The input collimator of the fibre-optical stretcher (16 in Fig. 3) is installed in the flipping mount so that one can easily switch without readjustment between the two configurations of the setup, for reproduction and transfer of the unit, and for calibration of the standard. The output collimator of the fibre-optical stretcher (18 in Fig. 3) is installed in the manner that allows the use of the same beam splitter for both setup configurations.

2.2.2 Measurement Method

The streak camera captures streak images of the picosecond pulse exiting the fibre-optical stretcher. These images are then transformed using the sweep calibration function to correct the sweep nonlinearity of the streak camera. The duration of the pulse in pixels on sweep coordinate scale is measured for each streak image according to the definition given in ISO 11554:2006. Ten consecutive measurements are conducted, which is sufficient for statistics. The result of the measurements equals to their arithmetic mean $(\Delta x)_m$. To obtain pulse duration value is units of time, the measured value in pixels is multiplied by the effective sweep coefficient k_0 determined during calibration of the standard: $\tau_m = k_0 \cdot (\Delta x)_m$.

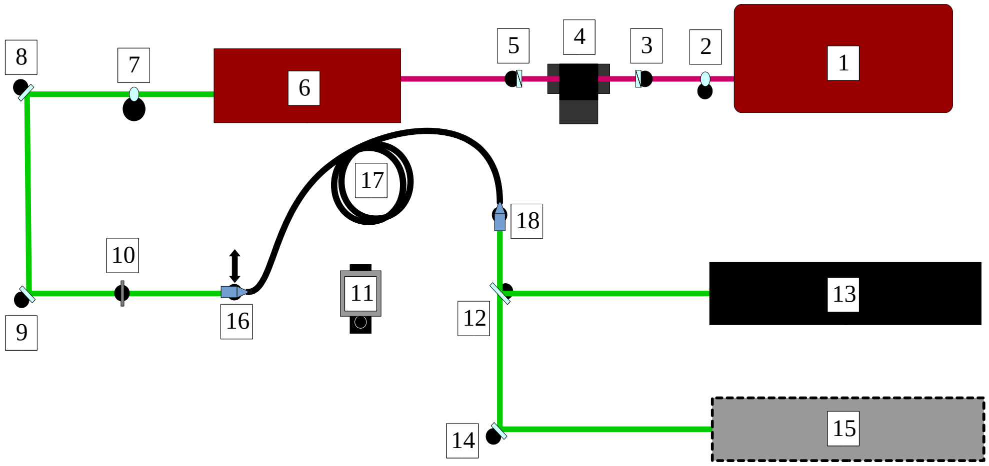

Figure 3. Optical scheme of the setup for reproduction of the unit of laser pulse duration by the standard, and transfer of the unit to another measurement instrument. Beside those mentioned in Figure 1 the following reference numbers are used: 16,18 – input and output collimators of the fibre-optical stretcher; 17 – optical fibre.

However this estimate of pulse duration contains systematic error caused by the influence of the streak camera instrument function. In general, the measured temporal intensity profile will represent a convolution of actual intensity profile with instrument function of the measuring instrument. In case the instrument function is known, one must perform deconvolution of the measured profile with the instrument function to obtain the actual intensity profile.

Preliminary experiments with the standard confirmed that the shape of the measured pulse from the fibre-optical stretcher and the streak camera instrument function both can be adequately fit by a Gaussian. In this case correction of the systematic error is possible without performing deconvolution, by the simple formula:

$$\tau = \sqrt{\tau_m^2 - \delta^2}\ , \tag{1}$$

where $\tau_m = k_0 \cdot (\Delta x)_m$ is the result of the pulse duration measurements, δ is the FWHM of the streak camera instrument function that was also determined during calibration of the standard.

Formula (1) is the measurement equation for the reproduction of the unit of laser pulse duration by the standard. The value of the unit τ is determined by the length of the fibre-optical stretcher so it can be set at will to fit the sweep duration of the streak camera, which is about 200 ps. In the present setup a 15 m long graded index multimode quartz optical fibre is used which produces an output pulse with duration of 42 ps. The FWHM of the instrument function of the streak camera is 2.5 ps. Thus the difference between measured pulse duration τ_m and its corrected according to the formula (1) value τ is less than 0.2%.

2.2.3 Uncertainty of Reproduction of the Unit

Uncertainty budget for reproduction of the unit of laser pulse duration by the standard is presented in Table 1. The estimates of the uncertainties in Table 1 are either the results of preliminary experiments with the standard or were deduced from the properties of the constituent parts of the standard and its operating conditions. Estimated combined standard uncertainty of reproduction of the unit is 2.7%.

Table 1. Uncertainty budget for reproduction of the unit of laser pulse duration by the standard.

Source of uncertainty	Type of evaluation	Standard uncertainty, %
Repeatability	A	1.4
Reproducibility	A	0.6
Calibration of the temporal sweep of the streak camera	A	2.2
Streak camera CCD sensor resolution	B	0.15
FWHM of instrument function of the streak camera	B	0.05
Thickness of the 2 mm spacer ring of the Fabry-Pérot etalon	B	0.03
Thermal variation of thickness of the Invar spacer ring of the Fabry-Pérot etalon corresponding to variation in temperature ±2°C	B	0.0003
Variation in refraction index of air corresponding to changes in environmental conditions within operating range	B	0.00015
Combined standard uncertainty		2.7
Expanded uncertainty (k = 2, 95% confidence)		5.4

2.3 Transfer of the Unit

Transfer of the unit to another measuring instrument or a secondary standard is provided by the use of beam splitter (12 in Fig. 3). The beam splitter divides the pulse energy in 50:50 ratio, so both the standard (by means of the streak camera) and other measuring instrument receive almost the same laser pulse. Slight deviation of the beam splitting ratio from its nominal 50:50 value doesn't matter as long as the intensity of the pulse falls within dynamic range of both instruments.

The method of transfer of the unit to another measuring instrument relies on the simultaneous measurement of duration of the same laser pulse coming from the fibre-optical stretcher by that instrument and by the standard. The value of the unit transferred to the measuring instrument assumes the pulse duration value as measured by the standard. Owing to the simultaneous measurement method used for transfer of the unit from the standard to another measurement instrument, the uncertainty of transfer equals that of reproduction of the unit.

In such a way the standard can also be used for verification of the measuring instruments for laser pulse duration. The verification is passed by the measuring instrument if the deviation of its measured pulse duration from the one measured by the standard doesn't exceed a certain limit imposed by the specification of that measuring instrument.

3. CONCLUSION

The principles of operation and the construction of the standard for laser pulse duration have been described. Preliminary experiments with the standard demonstrated that combined standard uncertainty of reproduction of the unit is below 3%. The final metrological properties of the standard will be measured at the next stage of the standard development which involves comprehensive metrological studies of the constructed standard. Plans for further improvement of the standard include the development of advanced measurement and control software as well as full automation of measurements and data processing.

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