Improved technique for picosecond pulse duration measurement based on second harmonic generation

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Abstract. In present paper we demonstrated an improved technique for characterization of ultra-short pulse duration (PD) based on second harmonic generation (SHG). We utilized Yb-doped fiber laser with picosecond duration of pulses as implementation of proposed technique and for estimating the accuracy of pulse duration measurement. KTiOPO₄ crystal was used for the purpose of second harmonic generation. We determined the duration of laser pulses by analysing the combination of signal intensities on input and output of SHG crystal. We observed experimentally error of pulse duration measurement less then 2%. We showed strong dependence between the average power of SHG and the duration of picosecond pulses.

1. Introduction and Background

In technological field ultrashort-pulsed (USP) lasers are actively used in micromachining, eye surgery, optical coherence tomography etc. [1, 2] Using of USP lasers as frequency divider to organize precise link between radio and optical frequencies is one of the important scientific applications [3, 4, 5, 6, 7, 8]. Wide spreading in industry requires better parameters stability: average power, pulse duration (PD), position of polarization plane, mode of laser generation. Commonly used average power stability systems are typical for modern CW lasers. USP lasers would use these systems also but power affecting on PD require additional subsystems. During long-term utilizing fiber USP lasers demonstrate undesirable PD shifts, which could lead to critical failure of the target process. Undesirable PD shifts could be detected and compensated by an embedded PD measurement system.

Among the various PD measurement methods, we can highlight the following as most popular: streak camera, intensity autocorrelator [9], interferometric autocorrelator (or fringe-resolved autocorrelation - FRAC) [10, 11], frequency-resolved optical gating (FROG) [12], GRENOUILLE [13], and spectral phase interferometry for direct electric-field reconstruction (SPIDER) [14]. PD measurement based on SHG effect is less accurate then last versions of mentioned methods, nevertheless we did a research to understand the maximum possible accuracy. Balance between simplicity and accuracy of improved SHG method makes this technique useful for practical applications.

Previous papers dedicated to SHG generation [15, 16] had no ideas to use SHG as a measurement method. Harmonic generation process for ultrashort pulses was well studied in [17, 18]. Experiment setup used in [19] was similar to our setup, but we utilize USP laser. Slow
photodiodes did not detect ultra-shot processes, however our technique of analyzing CW-signal leaded to improvement in accuracy.

2. Experiments
During long-term use of ultra-short laser we observed undesired PD shifts, which cause time-consuming equipment returns and corresponding financial losses for laser development companies. Detected shifts have unclear reasons, but they all are characterized by a time constant greater than 1 s.

The general idea of PD measurement by means of SHG is to simultaneously fix average intensity immediately before $I_{av}^{(1)}$ and after $I_{av}^{(2)}$ SHG crystal and to calculate the current PD value by use of measured intensities and initial calibration data.

Setup consisted of Yb-doped fiber laser (Master source) followed by fiber amplifier (Preamp) (figure 1). SMF-128 fiber fragment compensated dispersion induced by amplifier. Then radiation came to polarizer and beam-splitter, where light partly redirected to photodiode 1, but main intensity run to SHG crystal. Photodiode 2 fixed output SHG signal after filtering. Overall conversion efficiency in our setup was less than 0.1%, although efficiency of KTiOPO4 nonlinear crystal itself was about 1%. For more productive nonlinear elements, such as optimized crystals [20] or globular photonic crystals [21, 22], our method precision will rise.

The setup ensured that the PD after amplification was consistent with the laser output. Rotation of the polarization plane had a strong influence on SHG efficiency, as described by $I_{av}^{(2)} \sim \sin(2\varphi)$ where $I_{av}^{(2)}$ is the average intensity of the SHG signal and $\varphi$ is an angle between the incident light polarization plane and the crystal optical axis. To avoid this effect, a polarizer was used to convert the oscillation of the angular position of the polarization plane into average power oscillation. Since InGaAs photodiodes detected both 532 nm and 1064 nm, even 1% of the incident 1064 nm radiation entering the second photodiode was several times stronger than the SHG signal. An IR reflector passed the 532 nm beam through and deflected the parasitic beam. A special electronic board collects signals from both photodiodes simultaneously.

3. Results
By means of linear approximation, we determined the relationship between PD and SHG signal for constant 1064 nm radiation power. Amplifier closed loop controlled average intensity on the
Figure 2. Relative error between estimated and real PD (Each line means constant average power 1064 nm radiation)

SHG crystal input by means of photodiode with time constant $T_{pd}$.

$$I_{av}^{(1)} = \int_0^{T_{pd}} I(t) dt = const$$  \hspace{1cm} (1)

Dependance of SHG average intensity on PD was described by

$$I_{av}^{(2)}(\tau) \sim \frac{1}{\tau^2}$$  \hspace{1cm} (2)

We fixed new series with $G(\tau)$ representing a linear interpolation of SHG dependance on PD. We got each curve from one $I_{av}^{(1)}$ value from the range $R = (6.3mW; 8.3mW; 10.0mW)$. We found that there is a similarity in the form of the calculated curves for different $I_{av}^{(1)}$ values. After normalization, this relationship can be expressed as

$$k(\tau) = \frac{1}{N} \sum_{j=1}^{N} \frac{G_j}{\max[G_j]}$$  \hspace{1cm} (3)

The mismatch between the series of curves $G_j(\tau)$ and $k(\tau)$ was less than 0.01%. For better results $k_2(y)$ calibrations were measured on the upper limit of the SHG signal range. We found that the relative error while using $k(\tau)$ is 5 times less than in the interpolation calculation, with a maximum of 2% (figure 2).

4. Conclusion
We improved the simple PD measurement method based on SHG effect. We revealed clear relation between SHG average power level and PD. By means of utilizing of observed relation in PD processing we reached 2% accuracy level.
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