Accurate Measurement of High Extinction Ratios of Ultrafast Pulsed Sources

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Abstract—We present a technique to accurately measure the extinction ratio (ER) of pulses shorter than 10 ps and show that this technique is accurate for ER values from 20 to 50 dB. The technique is based on second-harmonic generation frequency-resolved optical gating. The ER of 1.8-ps pulses was measured and compared with a calculated value. The error between experimentally obtained value and the expected value is within 0.5 dB.

Index Terms—Extinction ratio (ER), frequency-resolved optical gating (FROG), optical pulses, second-harmonic generation (SHG).

I. INTRODUCTION

Optical pulse sources with a repetition rate of 10 GHz or larger are extremely important for high-speed optical-time-division-multiplexing (OTDM) systems that transmit at rates of 40 Gb/s or greater and also for high-speed optical sampling applications. In these systems, a high pulse extinction ratio (ER) is critical to minimize intersymbol interference (ISI) and the resulting interference noise between passively multiplexed pulses. Previously, Zhang et al. [1] characterized the interferometric noise in an OTDM transmission system and a 28-dB ER is required to keep the ISI penalty below 1 dB. Therefore, techniques to accurately measure high ERs are very important for OTDM systems.

The techniques implemented to date to measure the pulse ER have been based on an autocorrelator. In [2] and [3], two different autocorrelation traces were compared in order to estimate the pulse ER enhancement. In [4], the autocorrelation trace was fitted with a calculated autocorrelation function of Gaussian pulses. This approximation enabled us to calculate the pulse ER. The first two approaches were not able to accurately evaluate the ER and the measurement gave a raw estimate of the ER. The limitation of the last approach takes place when the real pulse shape cannot be well approximated by a Gaussian function which leads to a measurement inaccuracy.

The limitations of prior approaches can be overcome using a frequency-resolved optical gating (FROG) which yields both the pulse envelope and phase information [6].

In this letter, we demonstrate for the first time that FROG techniques can be used to accurately measure ER in excess of 20 dB of ultrafast pulses. We apply this technique to characterize pulses generated by a mode-locked fiber ring laser that outputs 1.8-ps pulses with 17.8 mW of average power and a pulse ER of 47.7 dB. The ER of the laser is intentionally degraded by adding a continuous-wavelength (CW) signal to the pulses and the ER measurement was repeated for different CW power levels. The obtained results were compared with calculated ER values and the error was lower than 0.5 dB.

II. THEORY

The optical field generated by a pulse source, as described in [1], is given by

\[ E(t) = \sqrt{P(t) + P_0} \exp[j(\omega t - \phi(t))] \]  

(1)

where \( P(t) + P_0 \) is the intensity envelope and \( \phi(t) \) is a random process of phase noise. In particular, \( P(t) \) is the time-dependent intensity of the ideal pulse, \( P_0 \) is a constant power term that limits the ER. The intensity evolution of such a signal is presented in Fig. 1. The formal definition for the ER is

\[ \text{ER} = \frac{\text{P}^{\text{peak}}}{P_0} \]  

(2)

where \( \text{P}^{\text{peak}} \) is the peak power of the optical field in (1).

Fig. 1. Temporal evolution of the power at the output of a limited ER pulse source.

The procedure that enables us to obtain the ER is based on the second-harmonic generation (SHG) FROG described in [5], which is based on the spectral resolution of the output from a noncollinear autocorrelator. The full intensity and phase evolution of an arbitrary ultrashort pulse are reconstructed from the FROG trace given by

\[ I_{\text{FROG}}(\omega, \tau) = \left| \int_{-\infty}^{+\infty} E(t)E(t-\tau)\exp(i\omega t)dt \right|^2 \]  

(3)

where \( E(t) \) is the pulse envelope and \( \omega \) is the frequency.
where $\tau$ is the intensity autocorrelator delay. The FROG algorithm is based on phase-retrieval algorithms and convergence occurs only when the support of the electric field is limited (see [6] for details). This constraint is not satisfied anymore when a pulse with limited ER is considered. For ER values larger than 20 dB, however, this limitation has not been a problem and convergence is attained.

The FROG algorithm returns the normalized intensity $P_{\text{norm}}(t)$ with a support much shorter than the period $T$. This way it neglects the constant power term in (1) over the entire period $T$. The peak power $P_{\text{peak}}$ of the pulse, necessary for the ER calculation, is related to the power of the SHG signal obtained by the experimental FROG trace when $\tau = 0$

$$\int_{-\infty}^{+\infty} I_{\text{FROG}}(\omega, \tau = 0) d\omega = (P_{\text{peak}})^2 \frac{1}{T} \int_{-T/2}^{+T/2} P_{\text{norm}}^2(t) dt. \quad (4)$$

Due to the limited support of $P_{\text{norm}}(t)$, the calculation of the integral in the right-hand side of (4) neglects the contribution of the constant power term in (1) outside the support of $P_{\text{norm}}(t)$. Such an approximation, however, is not relevant given an ER $> 20$ dB. $P_{\text{peak}}$ can, therefore, be easily computed solving (4).

In order to calculate $P_0$, the intensity evolution of the SHG signal when $\tau = T/2$ has to be considered

$$P_{\text{SHG}}(t, \tau = T/2) = |E(t)E(t - T/2)|^2 = P_0^2 + P_0 P_1(t), \quad (5)$$

$P_{\text{SHG}}(t, \tau = T/2)$ is a periodic signal of period $T/2$ and in (5) it is considered in a $T/2$ large interval centered around zero. The resulting average power of the SHG signal is related to the FROG trace by the following equation:

$$\int_{-\infty}^{+\infty} I_{\text{FROG}}(\omega, \tau = T/2) d\omega = 2P_0 P_1 + P_0^2 \quad (6)$$

where $P_1$ is the average power of the ideal pulse which can be obtained by $P_{\text{peak}}$ and $P_{\text{norm}}$. Solving the second-order equation in (6), the value of $P_0$ can be calculated. Finally, ER can be obtained by (2).

III. EXPERIMENT

The measurement process described previously was implemented to measure the ER of a mode-locked fiber ring laser that outputs an average power of 17.8 mW with repetition rate 10 GHz and central wavelength 1557.56 nm. The SHG FROG apparatus is based on a 5-mm BBO crystal with bandwidth large enough to measure 1-ps pulses. The spectrum at the output of the SHG crystal was measured by a grating spectrometer with a 2048 pixel charged coupled device detector resulting in a spectral resolution of 0.12 nm. The autocorrelator delay has a temporal resolution of 4 fs.

Fig. 2(a) shows an example 256 $\times$ 256 FROG trace with 2-ms integration time of the spectrometer. Software is used to retrieve the pulse intensity and phase from the FROG output and was found to give a retrieval error of 0.005. The frequency marginal of the FROG trace [7] was checked and the retrieved intensity and phase of the pulse are plotted in Fig. 2(b). The width of the reconstructed pulse is 1.8 ps. In order to accurately calculate ER, the integration time of the spectrometer was increased to 10 s and a measurement of the spectrum at the output of the SHG crystal was made with the delay $\tau = 50$ ps resulting in a measured ER of 47.7 dB. The integration time of 10 s was the maximum value that can be set on our spectrometer limiting the current apparatus to ER of 50 dB. The maximum measurable ER in general depends on the efficiency of the SHG nonlinear process and on the sensitivity of the spectrometer.

In order to check the accuracy of the ER measurement, a further experiment shown in Fig. 3 was performed. A CW laser was coupled to the pulse source through a 3-dB coupler with the purpose of degrading the ER of the resulting pulses. A variable optical attenuator was used to change the ER value and a polarization controller matched the polarization state of the two lasers. The interference between the two signals could affect the form of the electric field in (1). The ER values considered, larger than 20 dB, make the interference terms not relevant. The ER was evaluated using the proposed technique for different attenuation values. For each measurement, the expected value of ER was evaluated measuring the power contribution of the CW laser at the output of the coupler. The CW power in the case of null attenuation was 4.2 dBm. The average power of the pulse
laser at the output of the coupler was 7.6 mW and the equivalent peak power was 411 mW. The background signal that limits the ER of the pulse source added to the CW signal and a corrective term was considered when the expected ER was calculated. Fig. 4 shows a comparison of the expected and calculated ER. The two curves matched with an error lower than 0.5 dB. The wavelength of the CW laser was 1557.56 nm centered in the bandwidth of the pulse laser spectrum. This wavelength did not affect the results of the experiment. We repeated the same measurement for different wavelengths inside the bandwidth of the pulse laser spectrum and we checked no alteration of the measured ER. Fig. 4 shows also a curve obtained by simulation of the system in Fig. 1 and evaluation of the resulting ER. The obtained ER perfectly matches the expected ER as long as it is bigger than 20 dB. For lower values, there is an error in the simulated ER higher than 0.5 dB.

IV. SUMMARY AND CONCLUSIONS

An SHG FROG apparatus has been used for a complete ER characterization of a pulse source. The proposed procedure is able to estimate the optical ER of ultrashort pulse sources with an error lower than 0.5 dB and measure 20–50-dB ER of 1.8-ps pulses.

REFERENCES