ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TUPCC08

IMPROVING THE SENSITIVITY OF EXISTING ELECTRO-OPTIC SAMPLING SETUPS BY ADDING BREWSTER PLATES: TESTS OF THE STRATEGY AT SOLEIL

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Abstract

For improving the sensitivity of electro-optic sampling (EOS), several techniques are used. Operation of the set of polarizing elements "close to extinction" is a technique used routinely for obtaining high responsivity (i.e., a large output signal for a given input electric field). This technique is widely used for monitoring electron bunches in linear accelerators and FELs. We show that a simple modification of these EOS systems enables to increase further the SNR, by cancelling out the laser noise. The idea is to introduce a set of Brewster plates, following the idea Ahmed, Savolainen and Hamm [1] in the EOS path, and performing balanced detection. We present detailed tests of this type of upgrade on the PhLAM-SOLEIL EOS system, destined to studies of THz CSR pulse dynamics [2, 3].

INTRODUCTION: CLASSICAL SNR IMPROVEMENT METHODS AND THEIR LIMITATIONS

For recording ultrafast electric field transient in single-shot, a particularly efficient method consists in using the spectrally encoded Electro-Optic Sampling (EOS) [4,5,5–8]. The electric field transient is imprinted onto a chirped laser pulse, by electro-optic modulation. Then the output pulse is analyzed using a single-shot spectrum analyzer.

High Responsivity Using Near-Extinction EOS Setups

In order to reach high SNR, a popular way consists in operating the setup in a configuration known as *near extinction* EOS [9, 10] (Fig. 1a). In these conditions, an important limit to the SNR comes from the shot-to-shot fluctuations of the laser, which can be well above the shot-noise limit. This is particularly the case for laser systems with a fiber amplifier, which is known to add Amplified Spontaneous Emission noise.

Noise Cancellation Using Balanced Detection

Laser noise cancellation is possible using balanced detection [11–14] (Fig. 1b). However the combination with near-extinction (for reaching high responsitivety) is not trivial to realize.

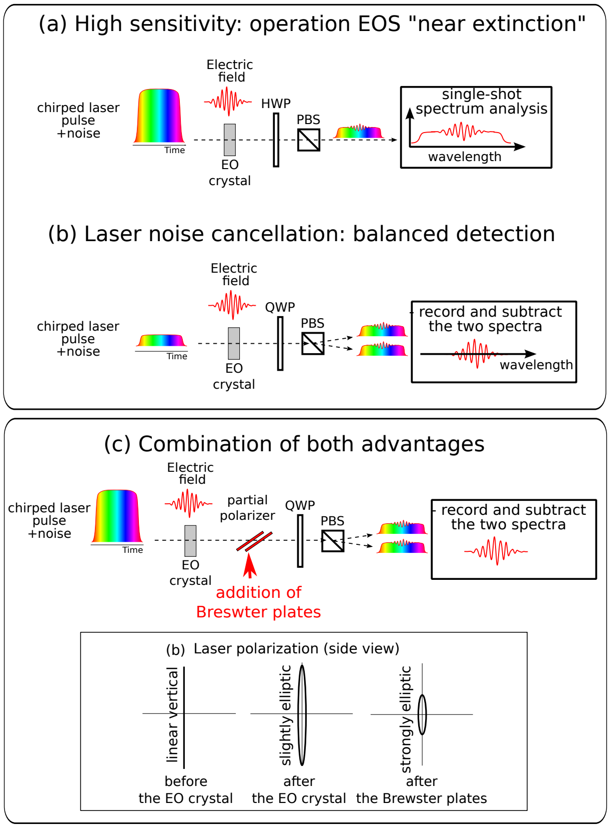

Figure 1: (a) and (b): classical EOS setups. In (a) operation near extinction can provide high responsivity (defined as the detected signal per unit electric field in the EO crystal). The balanced detection scheme (b) provides laser noise cancellation capability, but has a moderate responsivity. The EO setup (c) provides both advantages, i.e., high responsivity and laser noise cancellation. Lower inset represents the polarization states of the light in the setup.

PRINCIPLE OF THE METHOD

In a different context (scanned EOS), Ahmed Savolainen and Hamm demonstrated that the advantages of (i) near-extinction and (ii) balanced detection can be associated in a very simple way. The principle consists of introducing a partial polarizer (e.g., a set of Brewster plates) in a classical balanced detection EOS system, between the EO crystal and the polarizer [1, 1]. We tried to test this strategy in the case of single-shot spectrally-encoded detection. The basic principle is represented in Figure 1c.

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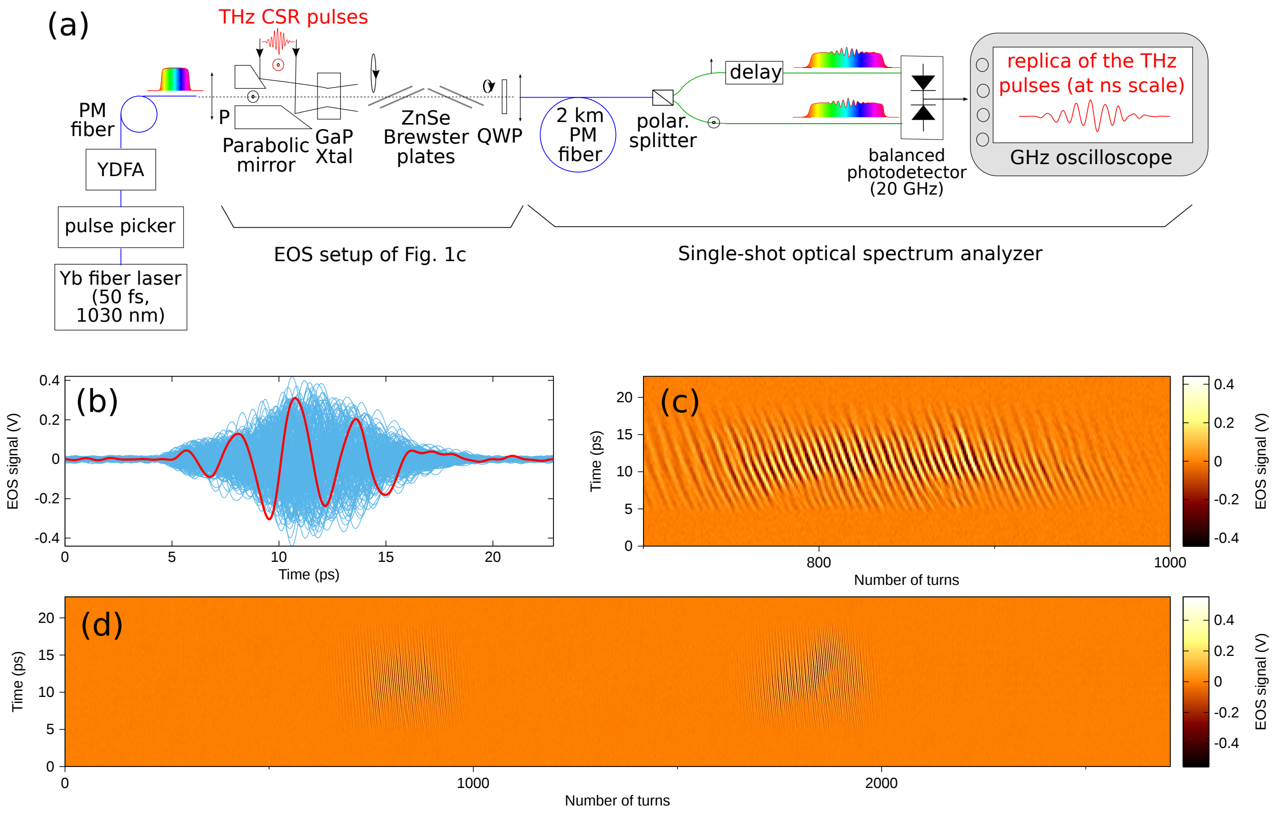

Figure 2: Results using the Brewster plate enhancement scheme. (a), Experimental setup. (b), Series of 250 EOS traces (blue) and example of a single pulse (red). (c) Same series of pulses represented as a colorscale diagram. (d), complete set of data displaying two bursts.

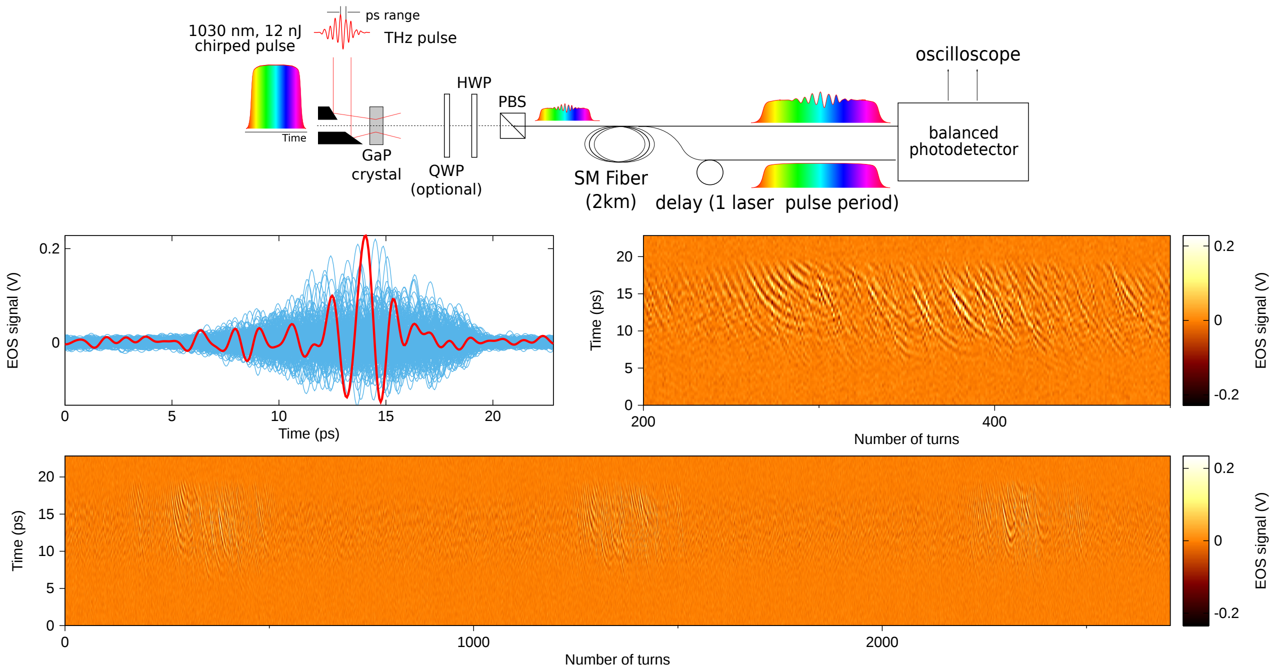

Figure 3: For reference, series of THz CSR pulses recorded using the classical *near extinction* setup (the scheme of Fig. 1a). (a) detailed setup. (b) series of 350 pulses, during a THz burst (blue curves), and example of single pulse (red). (c) The same series of pulses represented as a colorscale diagram, (c) complete set of data displayig 3 bursts. Note that the SNR is mainly limited by the laser source noise, which is visible between the bursts. Also, note the asymmetry in the shape of EOS signals in (b), which is due to second order distorsion (and not present in Fig. 2).

For a given optical power on the spectrum analyzer, the EO signal is proportional to $1/\sqrt{T}$, with T the power transmission of Brewster plates. This is formally similar to the "enhancement effect" of the near-extinction technique. However the setup of Fig. 1c provides two complementary outputs. Hence if we perform the difference between the two spectra, we expect to obtain also a noise cancellation effect.

TESTS AT SOLEIL

Details of the EOS Setup

We tested the strategy on the EO system destined to THz Coherent Synchrotron Radiation studies at SOLEIL. We basically realized the Fig. 1c system, but introduced an long (2 km) polarization-maintaining fiber between the quarter wave plate and the polarizer. With this setup (Figure 2), the spectra are obtained using the so-called Dispersive Fourier Transform technique (or time-stretch) [15–17]. After propagation in the fiber, the spectra are converted into a temporal signal which is recorded with a single-pixel photodetector. Apart from this specificity for the spectrum analysis, the system is equivalement to the setup of Figure 1c.

Results

A typical recordings obtained in normal alpha mode (user mode) at SOLEIL is represented in Figure 2b-d. Detailed measurements showed that the senstivity, i.e., the noise-equivalent input electric is of the order of 2.3 μV/cm/$\sqrt{\mathrm{Hz}}$ in the 0-300 GHz band. The signal to noise ratio is increased by a factor 6.75 with respect to the balanced detection scheme, see Reference [2] for detailed measurements. We have also displayed typical results obtained with our previous near-extinction setup in Fig. 3.

The detectivity enhancement (with respect to the classic balanced detection scheme) can theoretically reach a =18.9 with our setup, if the power incident on the photodetector can be kept at its optimal value. In this test, the available power (12 nJ per pulse) was too low (by a factor 4) to reach this a = 18.9 value. Further improvements can be thus made by increasing the laser power.

Another advantage of the Brewster plate method (with respect to the near extinction scheme) concerns the non-linearity. The transmission of the Brewster plates scheme does not present quadratic distorsion. This is different from the near-extinction scheme, whiich exhibits quadratic distorsion. We have not quantified this effect. However this difference is visible in Figures 2b an 3b. The superposition of EOS traces (blue curves) presents an asymmetry in the the near-extinction case, that is not present with the Brewster scheme.

CONCLUSION

The introduction of a set of Brewster plates in an EO system appears as a promizing alternative to the *near-extinction* scheme, as it enables a cancellation of the laser noise. It is also important to note that this strategy is not restricted to EO setups with time-stretch readouts, but should also be feasible with classical spectral encoding EO systems.

ACKNOWLEDGEMENTS

The work has been supported by the BQR of Lille University (2015). The work has also been supported by the Ministry of Higher Education and Research, Nord-Pas de Calais Regional Council and European Regional Development Fund (ERDF) through the Contrat de Projets État-Région (CPER photonics for society), and the LABEX CEMPI project (ANR-11- LABX-0007). Preparation of the experiment used HPC resources from GENCI TGCC/IDRIS (i2015057057, i2016057057).

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