Measurement Science and Technology

100 year anniversary
Measurement Science and Technology

TECHNICAL NOTE

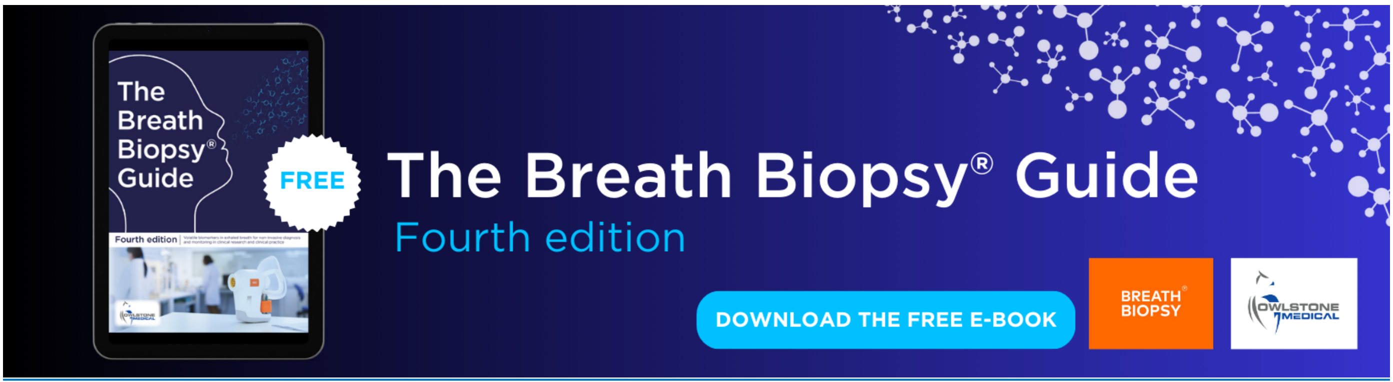
A simple, low cost interferometric autocorrelator with no moving parts

To cite this article: T J Kelly *et al* 2016 *Meas. Sci. Technol.* **27** 117003

View the article online for updates and enhancements.

You may also like

- A high-speed superconducting digital autocorrelator operating at 20.48 GHz
Steven B Kaplan and Henrik Engseth
- Accuracy of the duration estimates of ultrashort laser pulses using a single-shot second-order intensity autocorrelator
I.V. Kuzmin, S.Yu. Mironov and E.A. Khazanov
- Temporal characterization of laser pulses from JIGUANG-I laser facility with a compact dual function autocorrelator
Xia Jiang-fan, Wei Zhi-yi, Qiu Yang et al.



This content was downloaded from IP address 18.119.159.150 on 30/04/2024 at 00:28

IOP Publishing

Measurement Science and Technology

Meas. Sci. Technol. **27** (2016) 117003 (6pp)

doi:10.1088/0957-0233/27/11/117003

Technical Note

A simple, low cost interferometric autocorrelator with no moving parts

T J Kelly[1,2], S J Davitt[1] and J T Costello[1]

[1] School of Physical Sciences and National Centre for Plasma Science and Technology, Dublin City University, Glasnevin, Dublin 9, Ireland

[2] Department of Physics and Mathematics, University of Hull, Hull, HU6 7RX, UK

E-mail: thomas.kelly9@mail.dcu.ie

Received 29 March 2016, revised 30 August 2016
Accepted for publication 14 September 2016
Published 5 October 2016

Abstract

The design and implementation of a low cost interferometric autocorrelator with no moving parts is discussed. It is found that the device is optically simple, uses low cost components and self aligns. The device is used to measure the interferometric autocorrelation of an 800 nm Ti:Sapphire laser pulse produced from an 80 MHz oscillator. The theory and experiment of the design is discussed and compared to results from a commercial autocorrelator. The device is intended for use where pulse to pulse monitoring of the temporal duration is required.

Keywords: interferometric autocorrelation, ultrafast pulse metrology, Wollaston prism

(Some figures may appear in colour only in the online journal)

1. Introduction

The measurement of ultrashort laser pulses is some-what frustrated by the fact that electronic devices do not respond on a fast enough timescale. Thus, in the 1960s, techniques were developed based on cross and auto-correlation methods to solve the problem [1]. The basic tenet of auto-correlation is that, when there are no shorter pulses available, the best candidate to measure a laser pulse is the pulse itself. The auto-correlation of the electric field of the laser pulse with itself is equal to the Fourier transform of its spectral magnitude. However, measurement of the auto-correlation of the laser pulse intensity can be used to determine the laser pulse width if the shape is assumed or known. The basic principle of operation of intensity autocorrelation is to split the laser pulse into two replicas and measure the signal generated in a non-linear medium as one pulse is time delayed with respect to the other. The width of the measured signal is the product of the laser pulse duration with some deconvolution factor which depends on the pulse shape. If the pulses are combined non-colinearly in the non-linear medium, the resulting measured signal is characterised by an absence of background, and a smooth continuous signal. If the pulses are combined co-linearly in the non-linear medium, the process is known as interferometric auto-correlation. Here, the resulting signal contains four components: a background signal; a modulated version of the non-colinear signal; an oscillation at the fundamental pulse frequency and an oscillation at twice the fundamental frequency. Therefore, interferometric autocorrelation operates under the same principle of intensity autocorrelation but provides extra pulse information. In fact, there are numerous reports of interferometric autocorrelation being used together with a measurement of the pulse spectrum to obtain both the pulse intensity and phase or the pulse chirp [2, 3]. The complete pulse structure, both temporal intensity and phase, and spectral intensity and phase, can be measured using techniques like FROG [4], SPIDER [5] or many of their clever derivatives (like GRENOUILLE [6] or SEA-SPIDER [7]). However, for many applications in industrial or research environments, an accurate estimation of the intensity duration is sufficient.

Traditionally, something like a Michelson or Mach–Zender interferometer is used in both intensity and interferometric auto-correlation to split and delay the pulses time. However, there are some reports on the use of fixed interferometers which

 © 2016 IOP Publishing Ltd Printed in the UK

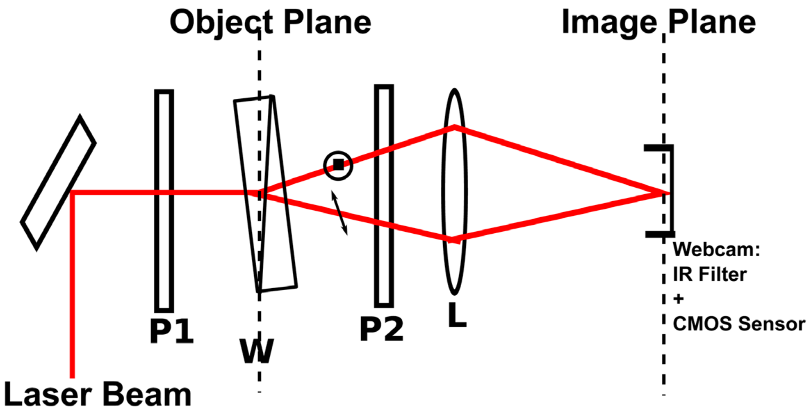


Figure 1. Optical setup for the interferometric autocorrelator.

result in faster measuring times and lower noise [8]. Similarly there has been much progress in auto-correlators which use two-photon detectors as both the non-linear medium and the method of detecting the signal [9]. These devices generally result in higher sensitivity. Similarly there are reports of birefringent beamsplitters being used to generate the optical path difference between the two pulse replicas [9, 10].

In this article, we present the design and demonstration of a simple, compact low cost interferometric autocorrelator with no moving parts. The design uses a Wollaston prism to act as an interferometer and a commercial web-camera is used as a two dimensional detector. Most commercial web-cameras (for example the Logitech WebCam Express, which was used in this study) consist of a two dimensional array of active pixels. These pixels are traditionally made of silicon. The spectral response of a silicon detector has an upper limit of roughly 1100 nm as this wavelength corresponds to an energy equal to the band gap of silicon. Thus, silicon based photodetectors are inherently sensitive to light in the mid-IR range of the electromagnetic spectrum. In a typical web-camera operation, this sensitivity outside the visible would cause unwanted image distortion and so, most commercial web-cameras are equipped with an IR blocking filter to limit the response of the camera to the visible range (400 nm–700 nm). For this reason, the web-camera consists of a 2D silicon photodetector array and an IR blocking filter. The sensitivity of the web-camera, then, at the wavelength of the laser used in this study (800 nm) is quite low. However, it was found that a non-linear process could be driven in the filter such that the sensitivity at 800 nm increased. A non-linear medium is a necessity for measuring the pulse width of ultrashort laser pulses by autocorrelation. Thus, the web-camera acts as both the non-linear medium and the signal detector. The resulting device is a low-cost, non-moving, single shot interferometric autocorrelator. The device would be useful in industrial applications where online monitoring of stable, relatively simple laser pulses is needed. In essence, this article combines the designs in two previous articles [9, 11]. In one of these articles [11], the Wollaston prism interferometer is used with a linear detector to produce a non-moving Fourier transform spectrometer. In the other article [9], a multiphoton detector is used together with a Wollaston prism to produce an interferometric autocorrelation measurement. However, in that article, the Wollaston prism was scanned spatially to produce the path delay between the two pulses as a function of the spatial position of the Wollaston prism. In this article, it is shown that both techniques can be combined to produce a new result: a single-shot, interferometric autocorrelation measurement with no moving parts.

2. Experiment

A commercial Ti:Sapphire oscillator (Coherent Micra 5) was used in this experiment as the source of laser pulses. The laser operated at its fundamental wavelength of 800 nm and generated laser pulses at a repetition rate of 80 MHz. A schematic of the non moving, interferometric autocorrelator is shown in figure 1.

The fixed autocorrelator is comprised of 5 optical components. A lens (L), two thin polarisers (P_1, P_2), a camera (CMOS sensor) and a Wollaston prism (W). The beam is initially vertically polarised. P_1 selects the component of polarisation at 45° to this and the beam then enters the Wollaston prism. A Wollaston prism is composed of two wedges of a birefringent material joined at their hypotenuse faces. They are joined in a such a way that their optic axes are perpendicular to each other and the beam direction. Thus, any linearly polarised beam will be resolved into two orthogonal components which emerge from the Wollaston prism with a divergence angle between them which is related to the angle of the wedges of the prism (θ). If the beam that enters the prism is polarised at 45° to the optic axes, the two emerging beams will be of equal intensity. The optical path difference between these two beams will change as a function of lateral displacement from the centre of the prism and is given by:

$$\Delta = 2x(n_e - n_o)\tan\theta \tag{1}$$

where x is the lateral displacement from the center of the prism. The time delay between the two pulses, as a function of x, can be calculated from equation (1). For the apparatus described here (a prism with dimension 2 mm (thickness) ×20 mm (height) ×20 mm (breadth), that was calculated to be ±1.4 ps for the two ends of the prism. A 100 mm focal length lens is used to image the interference plane of the fringes to the camera with a magnification of X1. The position of the polarisers is relatively unimportant as long as they are either side

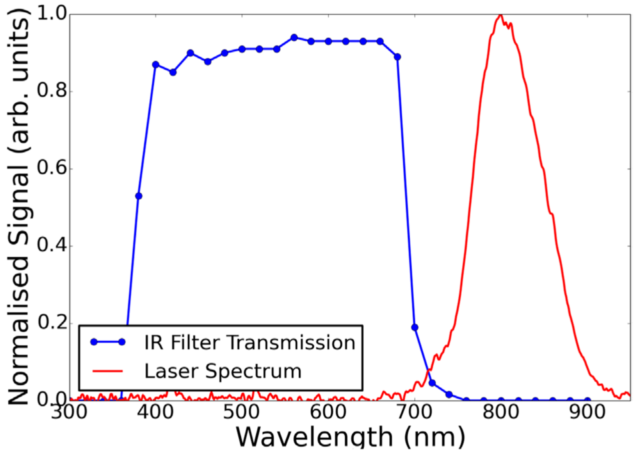


Figure 2. Spectral response of the IR blocking filter in front of the web-camera. The detected intensity was normalised to the spectral output (measured independently). The response plotted here does not take into account the spectral response of the imaging sensor.

of the Wollaston prism. The object plane of the lens is set to be roughly in the centre of the Wollaston prism and the web camera is placed at the image plane in order to observe clear fringes. This information allows the pixels on the camera to be converted to a time step (in the horizontal direction) and a spatial length (in the vertical direction). The spectral response of the camera was measured using a xenon lamp with a relative intensity spectrum that was known in the range 300–900 nm. A monochromator was used to scan the spectrum of the xenon lamp in the 300–900 nm spectral range at high resolution. The response was of the camera at different wavelengths in the range 300–900 nm is plotted in figure 2, normalised to the relative spectral intensity. Figure 2 shows that the camera is blind to radiation in the wavelength range of the laser beam used in this experiment. This is due to an IR blocking filter placed in front of the sensor during manufacture.

The non-linear response of the camera was measured in the following way: first, the modelocking procedure of the oscillator was deliberately interrupted to produce continuous wave radiation from the oscillator. The total (pixel integrated) response of the camera was measured as a function of laser power. The procedure was then repeated for modelocked laser pulses. The results are shown in figure 3.

The signal level from the camera (in counts) is scaled to give an output voltage by setting the maximum number of counts to 5 V. It can be clearly seen that the camera responds negligibly to continuous wave radiation and non-linearly to modelocked radiation over a wide power range. The minimum input power required to detect a signal in this device is dependant on many different factors and is likely to be device specific. Firstly, the absorption/reflectance of the optics used will reduce the optical power at the face of the detector. In this study, the routing mirror used was a broadband dielectric mirror designed with 99.99% reflectivity across the spectrum of the laser pulse. The polarizers (P_1 and P_2) were made of a polyvinyl alcohol dichroic plastic which had a transmission of roughly 80% across the spectrum of the laser pulse. The Wollaston prism was made of calcite which, again has high transmission across the laser spectrum and the achromatic lens was made of BK-7 glass. The other thing that will limit the detectability of the instrument is the IR filter and the camera. Firstly, the minimum required energy will be influenced by the noise of the camera. To estimate the noise on the camera, several 'dark' images were taken with no laser present. The minimum detectable signal is then defined as three times the standard deviation of the 'dark' signal. In this study, the minimum required input power was found to be 1 mW with a camera integration time of 10 ms. The efficiency of the non-linear process in the filter will also determine the minimum required input power. The efficiency was estimated at 8% by comparing the output signal of a camera with a filter in front with an identical camera with no filter at an input power of 1 mW. There is also a maximum input power allowed as evidenced by saturation of the modelocked graph in figure 3. The signal seems to saturate at 1.4 V (roughly 55 counts) which is below the saturation of the camera (255 counts). Thus, the saturation is most likely a saturation of the non-linear process occurring in filter. All of these parameters can be tailored by suitable choice of optics and detection hardware. However, the components chosen during this study give good response for input powers typical of most standard Ti:Sapphire laser systems. Similarly, the maximum input power will also be dependent on the damage threshold of the optics used. In this study, the damage threshold was far in excess of the input powers. The raw image obtained from the interferometric autocorrelator is shown in figure 4.

The interference pattern sits upon a slowly varying background. This is due to the spatial variation of the laser beam across the face arising from diffraction effects, unclean optics and the Gaussian profile of the beam. The contribution (I_{mod}) can be measured exactly by measuring two images: one with the second polariser aligned to the optic axis of one of the Wollaston prism wedges (I_0) and one with the polariser aligned to the other Wollaston prism wedge (I_{90}). A composite image is then formed by adding these two together in the form $I_{\text{mod}} = \sqrt{\frac{1}{2}(I_0^2 + I_{90}^2)}$. This is then divided out of the interferometric signal.

3. Theory

Typically, interferometric autocorrelation is realised by splitting an ultrafast laser pulse into two replicas and combining them co-linearly in some medium which responds non-linearly to the instantaneous electric field to the combined replicas. If the non-linear medium responds to the square of the combined input field, and the pulse is Fourier transform limited, the measured intensity as a function of delay (τ) is given by:

$$I_{\text{AC}}(\tau) = 1 + \mathrm{e}^{-2\ln(2)\left(\frac{\tau}{\delta t}\right)^2} + 4\mathrm{e}^{-\frac{3}{2}2\ln(2)\left(\frac{\tau}{\delta t}\right)^2}\cos(\omega\tau) + 2\mathrm{e}^{-2\ln(2)\left(\frac{\tau}{\delta t}\right)^2}\cos^2(\omega\tau) \quad (2)$$

where ω is the central laser frequency and δt is the underlying intensity pulse width. In the case of the Wollaston prism interferometer, the temporal delay τ between the two pulse replicas is a function of optical path difference

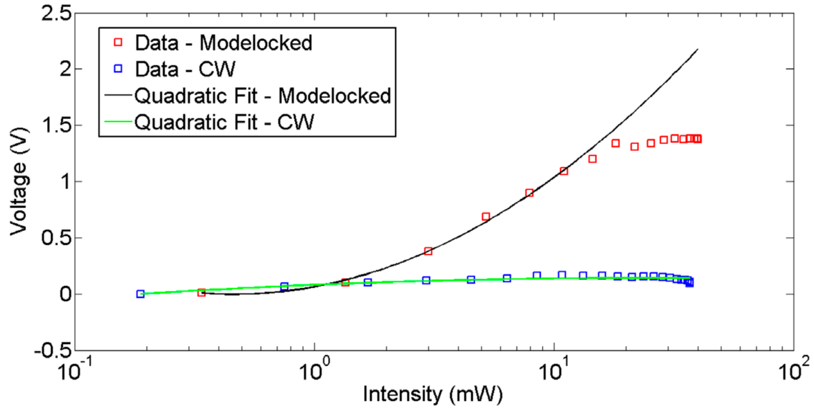


Figure 3. Spatially integrated response of the detector to both modelocked and CW radiation. Both datasets were fitted with a function of the form $f(x) = Ax^2 + Bx + C$. The case of CW radiation gave a non-linear parameter of $A/B = 0.2$ whereas for modelocked radiation A/B was 2.

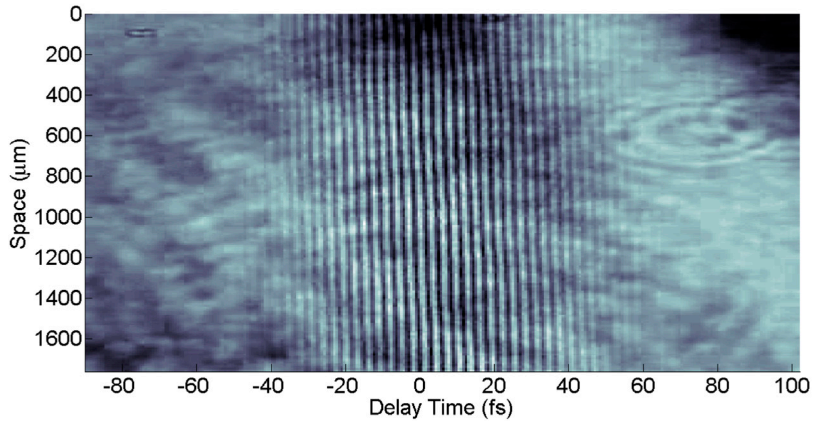


Figure 4. Raw image obtained with the optical setup.

between the two pulse replicas which is itself a function the pixel position across the camera. It can be written as: $\tau = \Delta/c = 2x(n_e - n_o)\tan(\theta)/c$. Thus, the measured signal across the face of the CMOS detector in the Wollaston prism interferometer is given by:

$$I_{\mathrm{AC}}(x,y) = A(x,y)\left[1 + \mathrm{e}^{-2\ln(2)\left(\frac{\tau}{\delta t}\right)^2} + 4\mathrm{e}^{-\frac{3}{2}2\ln(2)\left(\frac{\tau}{\delta t}\right)^2}\cos(\omega\tau) + 2\mathrm{e}^{-2\ln(2)\left(\frac{\tau}{\delta t}\right)^2}\cos^2(\omega\tau)\right] \quad (3)$$

$A(x,y)$ can be modeled as the sum as two spatially shifted TEM_{00} Gaussian profiles of the form:

$$A(x,y) = I_o T_1 T_2\left[\mathrm{e}^{-\frac{(x-\mathrm{d}x)^2}{2\sigma^2}+\frac{y^2}{2\sigma^2}} + \mathrm{e}^{-\frac{(x+\mathrm{d}x)^2}{2\sigma^2}+\frac{y^2}{2\sigma^2}}\right] \quad (4)$$

where I_o is the initial laser intensity and T_1 and T_2 are the transmission of polarisers P_1 and P_2. $A(x,y)$ has this form because, at the image plane of the lens, each laser pulse replica has the same spatial profile of the original laser beam but both replicas are shifted laterally in space due to the Wollaston prism. dx represents the spatial shift between the two replica beams and is given by the wedge angle approximation.

$$2\mathrm{d}x = f\theta(n-1) \quad (5)$$

where θ is the wedge angle of the Wollaston prism, f is the focal length of the lens and n is the mean refractive index of the prism. In reality, n takes a different value for both the e and o-waves which results in the plane of the interference pattern being rotated slightly. This is compensated for by rotating the Wollaston prism in the experiment. To retrieve the I_{AC} signal from the measured image, the parameter $A(x,y)$ can be measured by placing the second polariser at 0° and then 90° and measuring an image. The term $A(x,y)$ is then given by $A(x,y) = \sqrt{\frac{1}{2}(A_0^2 + A_{90}^2)}$. Both this and the measured I_{AC} image are vertically integrated. The background can then be divided out of the resulting signal to retrieve equation (2).

4. Results

Figure 4 shows a 2D image which contains the interferometric autocorrelation of the pulse in the horizontal direction and the spatial wavefront in the vertical. The image is integrated in the vertical direction to give the interferometric autocorrelation of the laser beam.

Figure 5 contains all the requisite features of an interferometric autocorrelation signal. Mainly, interference fringes and a peak-background ratio of 7:1 which is close to the theoretical expected value of 8:1. The reason for the less-than-optimal 7:1 ratio is due to a slight misalignment of the second polariser.

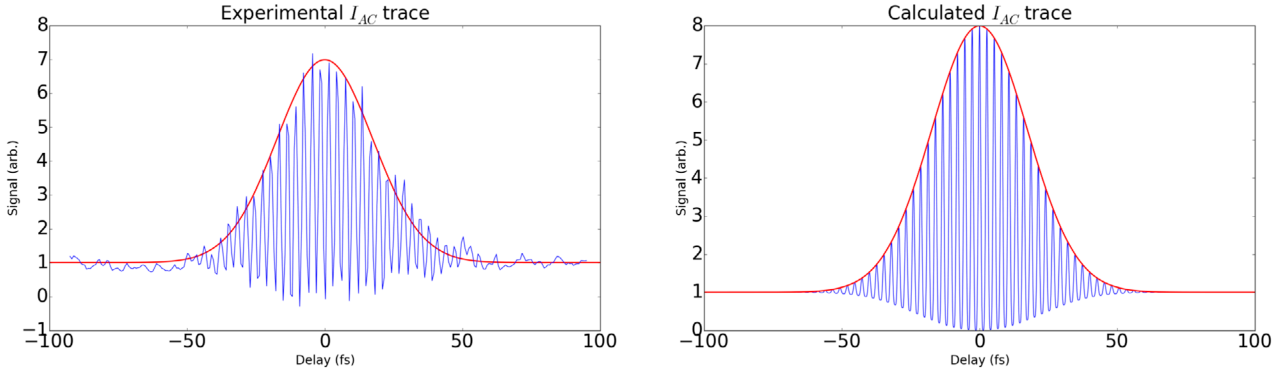


Figure 5. Interferometric autocorrelation of the laser beam with the Wollaston prism autocorrelator (left) for an input power of 50 mW at a rep. rate of 80 MHz. During acquisition, the integration time of the camera was at a minimum (10 ms) and the gain on the camera was set to zero. Calculated trace using equation (2) (right).

It is not expected to have a significant effect on the estimated pulse duration. The pulse width was extracted by fitting the data to equation (2) and extracting the fitted parameter δt. The fit gave a pulse width value of 31 ± 2 fs where the error bar was estimated from repeated measurements. This is compared to a measurement on two commercial devices. The first, a non-colinear intensity autocorrelator (APE pulse check) gave a pulse width value of 34 ± 3 fs and the second, a Swamp Optics Grenouille gave a value of 29 ± 0.5 fs. Both commercial devices are in agreement with the device presented here.

The minimum measurable pulse duration is ultimately limited by the broadening of the pulse through the optics and the time resolution of the non-linear interaction in the IR filter. The broadening of a Fourier transform limited pulse through a transmissive optic of thickness l is given by:

$$\frac{\Delta t}{l} = \frac{K\lambda^2}{\tau c^2}\left[1 + \Sigma_i \frac{B_i\lambda}{\lambda^2 - C_i}\right]^{3/2} \bigg/ \Sigma_j \frac{B_j C_j \lambda}{(\lambda^2 - C_j)^2} \qquad (6)$$

where K is the time-bandwidth constant for an assumed pulse shape while B and C are the Sellmeier co-efficients. Given the total thickness of the optics in the apparatus, the total pulse broadening percentage is estimated at 2.6% for an input pulse duration of 30 fs with central wavelength of 800 nm. It is interesting to consider the broadening through the Wollaston prism. In our calculations, we chose the refractive index at 800 nm to be the mean refractive index of the ordinary and extraordinary values. However, in truth the broadening will the different across the face of the beam. In our measurement however, the broadening due to the different refractive indices is negligible with respect to the total broadening. Similarly, the minimum measurable duration is limited by the duration of the non-linear interaction. In traditional, second harmonic or two-photon, detectors the interaction is instantaneous. In the study presented here, the nature of the two-photon process was investigated. Firstly, the IR filter is a thin coloured glass screwed to the front of the image sensor. The amorphous nature of such a filter makes it unlikely to produce efficient second harmonic radiation. Two photon fluorescence or two photon induced transparency are likely candidates for the nature of the non-linear interaction. Certainly, from testing several off-the-shelf cameras, the empirical evidence suggests that a suitable non-linear interaction of sufficient bandwidth is possible in most standard web cameras or, a stand alone IR-blocking filter made of optical Schott glass could be used.

5. Conclusions

The performance of a low-cost interferometric autocorrelator with no moving parts has been described. The device uses a Wollaston prism to introduce a spatially varying phase delay which is imaged onto a CMOS webcam. The detector, normally blind to 800 nm radiation, acts as a non-linear medium allowing interferometric autocorrelation to be performed, potentially in a single laser shot. The technique for extracting the pulse width from the measured signal was discussed including how to handle the slowly varying background that appears due to spatial modulation of the laser beam. It was shown that the extracted signal gives pulse widths that are in agreement with commercial devices. The ultimate result is a reliable, compact, self-aligning pulse width measurement device which is low cost. It would be suited in industrial environments where the pulse width needs to be monitored throughout a processes. It is worth noting that that the device is easily calibrated, not very sensitive to alignment and can easily be made single shot using a lower repetition rate laser (like a Re-gen amplifier) or, for high rep rate lasers, using a time gated ICCD with an appropriate filter or second harmonic crystal.

Acknowledgments

This work was supported by Science Foundation Ireland (Grant No. 12/IA/1742). Work associated with the FP7 EU COST Action MP1208, the FP7 Erasmus Mundus Joint Doctorate EXTATIC under framework partnership agreement FPA- 2012-0033 and the U.S. National Science Foundation PIRE Grant No. 1243490.

References

[1] Armstrong J A 1967 Measurement of picosecond laser pulse widths *Appl. Phys. Lett.* **10** 16–20

[2] Chen C W, Huang J Y and Pan C 2006 Pulse retrieval from interferometric autocorrelation measurement by use of the population-split genetic algorithm *Opt. Express* **14** 10930–8

[3] Hache F, Driscoll T J, Cavallari M and Gale G M 1986 Measurement of ultrashort pulse durations by interferometric autocorrelation: influence of various parameters *Appl. Opt.* **35** 3230–6

[4] Trebino R, DeLong K W, Fittinghoff D, Sweetser J N, Krumbugel M A, Richman B A and Kane D 1997 Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating *Rev. Sci. Instrum.* **68** 3277–95

[5] Walmsley I A and Iaconis C 1998 Spectral phase interferometry for direct electric field reconstruction of ultrashort optical pulses *Opt. Lett.* **23** 792–4

[6] O'Shea P, Kimmel M, Gu X and Trebino R 2001 Highly simplified device for ultrashort pulse measurement *Opt. Lett.* **26** 932–4

[7] Wyatt A, Walmsley I A, Stibenz G and Steinmeyer G 2006 Sub- 10 fs pulse characterization using spatially encoded arrangement for spectral phase interferometry for direct electric field reconstruction *Opt. Lett.* **32** 1914–8

[8] Gutierrez A, Dorn P, Zeller J, Kling D, Lester L F, Rudolph W and Sheik-Bahae M 1999 Autocorrelation measurement of femtosecond laser pulses by use of a ZnSe two-photon detector arrays *Opt. Lett.* **24** 1175–7

[9] Reid D T, Padgett M, McGowan C, Sleat W E and Sibbett W 1997 Light-emitting diodes as measurement devices for femtosecond laser pulses *Opt. Lett.* **22** 233–5

[10] Wasylczyk P, Wasilewski W and Radzewicz C 2004 Single-shot autocorrelator based on a Babinet compensator *Rev. Sci. Instrum.* **75** 2482–5

[11] Padgett M J, Harver A J, Duncan A J and Sibbet W 1994 Single-pulse, Fourier transform spectrometer having no moving parts *Appl. Opt.* **33** 6035