A compact Fourier transform spectrometer with no moving parts for laser induced breakdown spectroscopy

S J Davitt¹, J T Costello¹ and T J Kelly²

¹School of Physical Sciences and National Centre for Plasma Science and Technology, Dublin City University, Dublin 9, Ireland
²School of Mathematics and Physical Sciences, University of Hull, Hull, UK HU67RX

stephen.davitt2@mail.dcu.ie

Abstract. We report the development of a portable single-shot Fourier transform spectrometer for application in laser induced breakdown spectroscopy (LIBS) with a particular emphasis on remote or standoff LIBS. The device, based on a design by Harvey and Padgett[1], has a number of inherent features that give it performance advantages over a portable grating spectrometer, in particular a gain in signal to noise ratio (SNR). Tests with low-pressure discharge lamps show a gain in SNR of at least five times that of a traditional portable grating spectrometer in stand-off mode. In addition, the instrument has also demonstrated the ability to measure the spectrum from a short or ultrashort pulsed source in a single shot, e.g. a laser produced plasma.

1. Introduction

In conventional dispersive spectroscopy, the spectrum is measured directly in the frequency domain. However, with Fourier Transform (FT) spectroscopy a temporal/spatial interferogram is recorded. The spectral distribution of an incident source can be determined by the power spectrum of the FT of the interferogram recorded[2]. There are two main advantages associated with FT spectroscopy, namely the Fellgett and Jacquinot advantages.

The Fellgett (or ‘multiplex’) advantage[3] pertains to a FT spectrometer since all frequencies are simultaneously measured. This allows the signal to be recorded more rapidly or with better signal to noise performance, compared to dispersive (grating) spectrometers. The Jacquinot (or ‘throughput’) advantage[4] arises from the fact that a FT spectrometer does not require an entrance slit. The resolution of a FT spectrometer is dependent only on the total number of fringes or optical path difference recorded. Hence the throughput is limited only by the apertures and transmission of the optical components and can thus be much higher than grating spectrometers with entrance slits.

Both advantages ultimately lead to an expected increase in the signal to noise ratio SNR over traditional dispersive spectrometers, which makes FT spectrometers ideal for situations where low light levels are a feature of the experiment or application, such as those found in standoff LIBS measurements.

2. Prototype WPFT Spectrometer

The prototype FT spectrometer (figure 1) is based on the original work of Padgett et al. [1], [2], and records an interferogram in the spatial domain. The design employs a Wollaston prism, an optical component formed by bringing together two optical wedges (with angles α) of a birefringent material.
that are symmetric but have their optic axes orthogonal to one another and to the direction of propagation.

A Wollaston prism has two main properties: the first property is that when a single incident beam propagates through the prism the beam will split into two diverging beams that are orthogonally polarized. If the incident beam is unpolarised, or linearly polarised to lie in a plane oriented at 45° with respect to the optic axes, the resulting pair of diverging beams will also be of equal intensity[1]. The second property is that for an incident beam of finite width, a phase shift $\delta$ is introduced at a distance $D$ from the centre of the prism, a linear phase shift across the width of the beam can be expressed as:

$$\delta(D) = \frac{2\pi}{\lambda} \cdot 2D\Delta n \tan(\alpha) \quad (1)$$

Where $\lambda$ the wavelength of the incident beam, $\Delta n$ the birefringence of the wedge medium ($n_e - n_o$), and $\alpha$ the angle of the two wedges. This linear phase shift creates an interference plane within the prism that, when imaged through an analyser polariser set at 45°, will form straight line fringes as the beams will constructively and destructively interfere. This spatial interferogram is the basis of the Wollaston prism Fourier transform (WPFT) spectrometer.

In order to analyse the resulting interferogram images, a MATLAB™ program was developed, the program converts the images to ASCII values and vertically bins this data to form a 1-D interferogram. The power spectrum can be obtained by using the built-in fast Fourier transform (FFT) function and the axis can then be transformed to wavelength $\lambda$ using the equation:

$$\lambda = \frac{2Nx\Delta n \tan \alpha}{i_\lambda M} \quad (2)$$

Where $N$ is the number of pixels, $x$ the width of the pixels, $M$ the magnification of the system and $i_\lambda$ indicates the spatial frequency $v_d$ such that $i_\lambda = v_d N x$.  

**Figure 1.** Photo and corresponding schematic of the prototype WPFT spectrometer in the linear configuration. The system is housed in a Thorlabs™ 30 mm cage system with one-inch optics making the system compact and rugged.
3. Results
A signal to noise (SNR) comparison was set up to compare the prototype WPFT spectrometer against a portable grating-based spectrometer (Stellarnet® EPP2000). A discharge bulb (Na / Cd) was located at one end of an optical table and the spectrometer placed at the other end, ~1.2 m away. A pair of polarizers $P_1$ and $P_2$ were used as a variable attenuator; $P_2$ was kept at a fixed angle, aligned with the polariser at the entrance to the WPFT spectrometer.

![Figure 2](image.png)

**Figure 2.** A) Comparison of SNR values for WPFT (red) and Stellarnet (blue) spectrometers, along with 1% transmission Na spectra for B) WPFT and C) Stellarnet.

**Figure 2A)** shows a comparison of the SNR values for the prototype WPFT spectrometer and the Stellarnet. The prototype WPFT spectrometer was found to have an average five times greater SNR compared to the Stellarnet grating spectrometer. This enhancement in SNR allows the signal to be distinguished from the noise at significantly lower light levels in the prototype WPFT spectrometer than the Stellarnet spectrometer, as shown from the 1% transmission data in **Figure 2B)** & C).

4. Conclusions
We have developed a prototype WPFT spectrometer which shows strong promise as a compact spectrometer for low light applications. The prototype WPFT spectrometer was shown to have a greater throughput than the Stellarnet® EPP2000, a comparable commercial grating-based spectrometer with a current improvement in SNR of a factor of $\sim 5 \times$. Additionally, the prototype WPFT spectrometer has been shown to be capable of single-shot acquisition of laser plasma spectra, indicating the ability for its deployment in LIBS applications.

**Acknowledgements**
We acknowledge support from Science Foundation Ireland under grant numbers: 12/IA/1742 & TIDA/2452, and the EU FP7 EMJD Programme ‘EXTATIC’ under framework agreement FPA-2012-0033.

**References**
[1] Harvey AR 1994 *Am. J. Phys.* 62, 1033
[2] Padgett MJ, Harvey AR, Duncan AJ and Sibbett W 1994 *Appl. Opt.* 33, 6035
[3] Fellgett P 1958 *J. Phys. le Radium*, vol. 19, 187
[4] Jacquinot P 1954 *J. Opt. Soc. Am.* 44, 761