Institution: University of Oxford

Unit of Assessment: 9 – Physics

Title of case study: [8] Measuring ultrashort laser pulses: LX SPIDER

1. Summary of the impact

Invented at the University of Oxford, an instrument for measuring the temporal shape of ultrashort laser pulses has delivered new capabilities for users and manufacturers of short-pulse lasers. The device, the LX SPIDER, is smaller, cheaper and more sensitive than its predecessor. Its impact has been realised by licensing patented technology to APE GmbH, who brought the LX SPIDER to market in 2008. Customers are from industrial and research institutions globally and the device has brought benefits to users in a variety of sectors including materials processing and biomedical diagnostics. It is also used by manufacturers of pulsed lasers in the specification, verification and installation of their laser products.

2. Underpinning research

The research implements, in a new and simpler way, the concept of spectral-shearing interferometry, a means to use nonlinear optics to determine the electric field envelope of an optical pulse using a deterministic algorithm. In its original incarnation, the Spectral Phase Interferometry for Direct Electric field Reconstruction (SPIDER) method was developed by Professor Ian Walmsley while at the University of Rochester.

The SPIDER technique requires a pair of pulses (the unknown input or 'test' pulse and a time delayed copy) and another pulse, derived from the same input pulse, which is strongly temporally broadened ('chirped'). A nonlinear interaction, sum frequency generation, between the long chirped signal and the test pulses, within a crystal, results in a frequency shift between the pair. The optical spectrum of the combined signal of the two pulses reveals the spectral phase, as a function of frequency, and thus complete pulse characterisation.

Although the SPIDER technique worked well, there were a number of features that if simplified would make the instrument smaller, more robust and more sensitive. After his arrival in Oxford in 2001, Walmsley set about simplifying the design. His research at Oxford produced a series of improvements resulting in a device that was smaller and easier to integrate into existing laser systems, which enabled its uptake across a wider group of users.

Walmsley realised the device could be made significantly simpler by reconfiguring the nonlinear optical process used to generate the spectral shear (that is, the differential frequency shift between two replicas of the test pulse spectrum). He designed a phase-matching arrangement that enabled the spectral shearing to be done in a single step with one crystal, without needing the chirped signal [1]. The key concept, group-velocity matching, was also shown theoretically to be very generally applicable to all nonlinear optical processes [2]. Group-velocity matching eliminated the need for the chirped pulse and therefore the optics that produced it, including a bulky and inefficient pulse stretcher [3,4].

In SPIDER, the crystal length was limited by the chirped signal, which travelled through the crystal at a different speed to the other two pulses and thus short crystals were used to minimise blurring in the spectral shear. By removing the need for the chirped signal, all pulses travel with the same velocity in a single crystal. Walmsley realised he could then use a longer crystal to perform the sum frequency generation, which would result in a dramatic increase in frequency conversion efficiency, and thus improve the sensitivity of the device. The long crystal (LX) method had a further advantage that the longer, thicker crystals were more robust and cheaper.

The research was led in Oxford by Professor Ian Walmsley (2001 – present) with Gorza (postdoctoral researcher 2005 – 2007), Wasylczyk (postdoctoral researcher 2006 – 2007) and research students Kosik-Williams and Radunsky.

The improvements from the Oxford research described in [2], [3] and [4] culminated in a new technique, named ARAIGNEE, which was patented in the US (US7599067, filed 2006, granted 2009) and in the EU (EP1886107, filed 2006, granted 2011). The inventors were Walmsley, Gorza and Radunsky and the patent was filed by Isis Innovation, the University of Oxford's technology transfer office.

3. References to the research (Oxford authors, * denotes best indicators of quality)

*[1] Radunsky A, Kosik Williams EM, Walmsley IA, Wasylczyk P, Wasilewski W, U'Ren AB and Anderson M, (2006), Simplified spectral phase interferometry for direct electric-field reconstruction by using a thick nonlinear crystal, *Optics Letters*, 31, doi: 10.1364/OL.31.001008, citations: 16 (Scopus).

[2] Gorza S-P, Radunsky AS, Wasylczyk P and Walmsley IA, (2007), Tailoring the phase matching function for ultrashort pulse characterization by spectral shearing interferometry, *Journal of the Optical Society of America B*, 24, 2064, doi: 10.1364/JOSAB.24.002064, citations: 3 (Scopus).

*[3] Radunsky AS, Gorza S-P, Wasylczyk P and Walmsley IA, (2007), Compact spectral shearing interferometer for ultrashort pulse characterization, *Optics Letters*, 32 181, doi: 10.1364/OL.32.000181, citations: 9 (Scopus).

*[4] Gorza S-P, Wasylczyk P and Walmsley IA, (2007), Spectral shearing interferometry with spatially chirped replicas for measuring ultrashort pulses, *Optics Express*, 15, 15168, doi: 10.1364/OE.15.015168, citations: 10 (Scopus).

4. Details of the impact

The ability to monitor and optimise the operation of lasers simply and reliably is important in many sectors and for some problems it is essential to know the temporal shape of the pulse. Walmsley and his group knew that a new device would have commercial appeal if they could reduce its size so it became smaller than the laser itself, and simple and reliable enough to be used by non-specialists. This demanded a simplified design.

The research at Oxford resulted in a number of commercial advantages of this technique over its predecessor:

- The reduction in optical components by eliminating the need for chirped pulses
    - reduced the device's physical size to less than that of a shoebox (10 times smaller).
    - simplified the installation process.
    - reduced the cost of fabrication.
    - increased the operational lifetime.
    - enabled its use by non-expert users.
- The use of a longer crystal
    - increased the sensitivity by a factor of 10 (pulse lengths of 16fs – 300fs can be measured).
    - improved the robustness.

New product brought to market

The Oxford research was commercialised through an exclusive license to German company, APE GmbH. APE specialise in devices for generation, manipulation and measurement of ultrashort laser pulses. APE have 55 employees, and sell products for the ultrafast laser market, directly and through distributors (e.g. Vereon, Newport, Thorlabs, Photonics Industry) in 40 countries.

Building on the licensed technology, APE introduced automatic calibration further simplifying the design. The new device, LX SPIDER, was brought to market in May 2008. The product is supporting a small group within APE that is dedicated to laser pulse metrology and the LX SPIDER represents between *[text removed for publication]* of APE's total sales. It retails at approximately *[text removed for publication]* and *[text removed for publication]* units have been sold to large and small companies as well as research institutions [A]. LX SPIDER is now the most common commercially-available method for full characterisation of the electric field of ultrashort laser pulses.

Benefits to laser manufacturers

Due to the commercialisation of the Oxford research and subsequent commercial availability through APE of the LX SPIDER, laser performance can now be specified more completely and easily than was possible a decade ago. Specification of the pulse shape, as well as its duration, in order to verify that the pulse is as short as possible is now routinely expected by buyers of lasers.

Companies who manufacture and sell lasers have used the LX SPIDER to specify their lasers and incorporated its use into their verification protocol. For example, Coherent Inc., one of the largest laser manufacturers and a leading producer of short pulse lasers and amplifiers, uses LX SPIDER units as a diagnostic tool in their R&D to verify laser operation, to adjust the laser configuration before shipping and during installation.

Coherent said that the LX SPIDER *"not only gives the pulse duration, but also spectral phase information, which simplifies and streamlines the alignment of compressor parameters in order to achieve best possible compression of amplified pulses. Spectral phase information also allows for a fast identification of possible issues with optics coatings, that are not meeting our specs, or even mirror surface flatness issues on optics that see spectrally spread beams."* [B]

Benefits to other end users

Ultrashort optical pulses are used in many applications, including advanced microscopy, materials processing (including photonic components for communication and sensing) and biomedicine. A method for pulse characterisation provides end users with more reliable processes and results. Where high levels of precision are required, introducing an LX SPIDER into the experimental configuration has allowed the user to adjust the optical pulse accurately.

A major market for the LX SPIDER is the commercial research laboratory sector where it is used by those performing molecular spectroscopy and microscopy, including the study of molecular dynamics in physical chemistry, transport studies in biology and for developing solar cells.

Another important set of applications is in nonlinear microscopy, used especially in biology. Knowing and controlling the shape and duration of the ultrashort optical pulses used in these techniques is vital to the generation of high-quality images, since the efficiency of the nonlinear processes that underpin these techniques depends on the peak intensity of the input laser pulses.

5. Sources to corroborate the impact

[A] Letter from Sales Manager at APE GmbH (held on file) confirms sales and licensing information.

[B] Statement from Senior Development Engineer at Coherent Inc. (held on file) confirms Coherent's use of the LX SPIDER in their R&D and production.