Quicken the PULS

Dr Lingze Duan established the Precision and Ultrafast Light Sciences group in 2007 to study the properties of light waves using ultrafast lasers. His work has led to new knowledge of light at its most fundamental level

Can you briefly explain the motivation behind your establishment of the Precision and Ultrafast Light Sciences (PULS) group?

Some of the most exciting frontiers in optics/photonics involve precise control and manipulation of the fundamental properties of light waves. These include, for example, ultrastable lasers, optical clocks, optical frequency combs, femtosecond and attosecond sciences, quantum communications, etc. The establishment of PULS was motivated by our recognition of this upcoming trend in research that focuses on high-precision light wave control and measurement, especially associated with ultrafast lasers.

Why have optical frequency combs (OFCs) been such an exciting development in the area of optical frequency metrology, particularly for the PULS group?

An OFC is a versatile tool. It can generate very short femtosecond-scale optical pulses so that in the time domain it provides fine temporal resolution. Additionally, an OFC's pulsing rate and optical phase can be directly stabilised by an atomic clock, which translates to an extremely high frequency stability – orders of magnitude better than conventional technologies. Therefore, in the frequency domain, an OFC can work as a frequency reference or 'ruler' to calibrate other light sources. It can also serve as a carrier for frequency references or 'clocks' in remote clock synchronisation. It is this versatility that attracts our interest, and much of our research activities focus on exploiting different OFC capabilities in novel applications.

You have been investigating optical sampling by laser cavity tuning (OSCAT) using your OFC facility – the Femtosecond Laser Frequency Comb (FLFC) lab. What is OSCAT and how does dynamic OSCAT differ?

OSCAT is a novel technique that utilises the fast cavity tuning capability of a femtosecond laser to achieve a rapid, large-depth tuneable optical delay. Such a tuneable optical delay is universally needed in optical interferometry, optical metrology, tomographic imaging and spectroscopy.

When OSCAT was first proposed in 2010 (by another group), it was theoretically described using a 'static' model, neglecting the fact that in reality the cavity tuning has to be done continuously. The 'dynamic' theory treats the cavity tuning as a continuous process and, therefore, is a more generic description of the technique and reveals some of the key features of OSCAT that were previously missing.

In 2013, you received a National Science Foundation Faculty Early Career Development (CAREER) Award. What are you hoping to achieve with the grant?

The scientific objective of the CAREER project is to develop a technology that allows for easy measurement of the carrier-envelope phase (the so-called absolute phase of light) with semiconductor devices. This phase represents a new way to define an optical phase. If we can conveniently measure it, we'll be able to better control it.

This can potentially open a new paradigm in many important fields, such as optical communications and optical sensing. Unfortunately, the current technology of probing the carrier-envelope phase is very costly and complicated – that's a problem we hope to address with this project. Additionally, we hope to take this opportunity to really understand the ultrafast coherent processes in semiconductor nanoparticles and develop a long-term research thrust on ultrafast nanophotonics at the University of Alabama at Huntsville (UAH).

The PULS group is exploiting the new UAH Ultrafast Nanophotonics Lab to study ultrafast interactions between optical pulses and semiconductor nanoparticles. Why are they so interesting?

In general, ultrafast nanophotonics is interesting because never before have we had a chance to work with a solid-state system so confined in all four dimensions of space-time. To begin with, semiconductor nanoparticles (quantum dots) have drastically different properties compared with their respective bulk materials, because their small sizes lead to highly quantised electronic energy structures. You can imagine how these nanoparticles interact with electromagnetic waves is very different from how bulk semiconductors would. Now, when we factor in the extremely short electromagnetic pulses (femtosecond laser pulses), we are looking at very fast electronic dynamics in these structures. Rich new physics is expected from such dramatic interactions. Our current focus on phase-sensitive carrier population inversion is only one of the many interesting topics in this emerging field.

On which areas of research will you be centring your gaze in the future?

Our research in the next few years will primarily focus on three areas: precision photonics, infrasonic fibre-optic sensing and ultrafast nanophotonics. In addition, we and our collaborators in China plan to investigate ultrafast photoelectron generation and ultrafast quantum communications.

A light less ordinary

Optical scientists and engineers based at **The University of Alabama in Huntsville** are capitalising on their state-of-the-art facilities to explore the nature of light and expand its applications

PULS' KEY RESEARCH ACHIEVEMENTS

- **Free-space transfer of optical frequency combs (OFCs)** – Duan and his students proposed the idea of remote synchronisation of clocks through free-space transfer of OFCs, and they reported the first experimental demonstration of OFC transfer in open atmosphere. This work has recently generated considerable interest in laser-based free-space clock distribution, as it provides a viable solution to space-terrestrial network synchronisation and GPS-free navigation
- **Optical sampling by cavity tuning (OSCAT)** – The Femtosecond Laser Frequency Comb facility has served as the light source to realise cavity tuning in the development of OSCAT by the PULS team, a technique that can potentially achieve a very fast tuneable optical delay (up to 100 kHz) with a large scan depth (eg. centimetres). Duan's dynamic theory for OSCAT and experimental demonstration of its application in remote target tracking and ranging, optical coherence tomography and 3D surface profiling has dramatically advanced the field
- **Optical fibre sensors (OFS)** – OFS are sensitive, compact, flexible and stable and have thus found numerous applications in measuring strain, temperature, pressure and other quantities. Duan has developed a thermomechanical theory to describe the fundamental thermal noise in optical fibres. He and his colleagues are experimentally probing the thermomechanical noise of optical fibres at very low frequencies (infrasonic region). This work could potentially lead to ultrasensitive OFS, and addresses some of the fundamental questions regarding the ultimate capabilities of these devices

FAMOUSLY DESCRIBED AS a 'solution looking for a problem' when first being engineered in the mid-20th Century, the laser has since found utility in a broad range of disciplines and sectors, pervading modern life in various ways, from supermarket barcode readers to industrial welding. Alongside the laser's incessant proliferation of applications, scientists and engineers have also been amassing an impressive array of types of lasers for various uses.

One particularly useful type of laser for many cutting-edge scientific investigations is the femtosecond laser. Such devices are capable of emitting extremely short pulses that last only a few millionths of a nanosecond, and are thus apt for ultrafast science.

Having developed femtosecond titanium-sapphire lasers at Massachusetts Institute of Technology, Dr Lingze Duan is ideally positioned to utilise these devices through research conducted within the Precision and Ultrafast Light Sciences (PULS) group at the University of Alabama in Huntsville (UAH). Established in 2007, PULS investigates a wide variety of ultrafast optics subjects, including precision control, measurement and transfer of light.

ON THE PULS

Although excellent progress was made in the first few years of PULS' existence, the current decade has been particularly fruitful for the group, seeing impressive and significant leaps in terms of both facilities and insights. Under a 2011 project funded by the National Science Foundation (NSF) Major Research Instrumentation Program, Duan and colleagues succeeded in establishing a new versatile, broadband light source and laboratory – the UAH Femtosecond Laser Frequency Comb (FLFC) facility – one of only a select few in the US equipped with an optical frequency comb (OFC) laser.

Research at the facility is focused around three areas. First, the group is working to exploit the exceptional precision of the OFC laser in remote transfer of optical frequency references via free space. They are also using the facility to develop optical sampling by laser cavity tuning, a technique with diverse and important applications. In the third and final area, PULS scientists aim to deepen their understanding to the fundamental limit of optical fibre sensors by directly probing the intrinsic thermal noise in optical fibres with lasers stabilised by FLFC.

COLLABORATION AND COMMUNICATION

Not only is this lab state-of-the-art in terms of equipment, but the combination of the PULS team's expertise and that of collaborators from several other labs housed in the same Optics Building – linked to FLFC by fibre optic cables for convenient delivery of laser output – means interdisciplinary collaborative projects have been pursued at an unprecedented pace. The instrument and resultant research outputs have also attracted the attention of additional collaborations from around the US. For instance, the NASA Marshall Space Flight Center; US Army Aviation & Missile Research Development & Engineering Center; and Optical Sciences Corporation are already involved in designing future research projects relying on the FLFC instrument.

Further to this, FLFC has become an education and training hub for UAH. Numerous graduate and undergraduate students and visiting scholars have been directly involved in research activities at the lab, and many prospective students and schoolchildren have visited, helping both short- and long-term recruitment to the University.

A CAREER BATHED IN LIGHT

More recently, in 2013 Duan and colleagues led the creation of the Ultrafast Nanophotonics Lab (UNL). Mainly funded by Duan's NSF Faculty Early Career Development (CAREER) grant named 'Semiconductor Detectors for Direct Probing of the Absolute Phase of Light', the facilities at UNL will provide PULS scientists with the opportunity to study the ultrafast interactions between femtosecond optical pulses and semiconductor nanoparticles, also known as quantum dots.

The central equipment of the lab is capable of generating pulses that are among the shortest optical bursts in the world. This capability is allowing the team to investigate the topic of phase-sensitive carrier-population inversion, a phenomenon whereby quantum dots are left on different energy states by pulses with different optical phases. If shown to exist, phase-sensitive carrier-population inversion could lead to semiconductor detectors of the so-called 'absolute phase' of light – an extremely important parameter in the march beyond current femtosecond science towards attosecond and zeptosecond scales.

IMPACT AT DIFFERENT SCALES

The impact of this UNL research could be felt around the world, allowing simple, low-power, low-cost and integrateable absolute phase detection based on

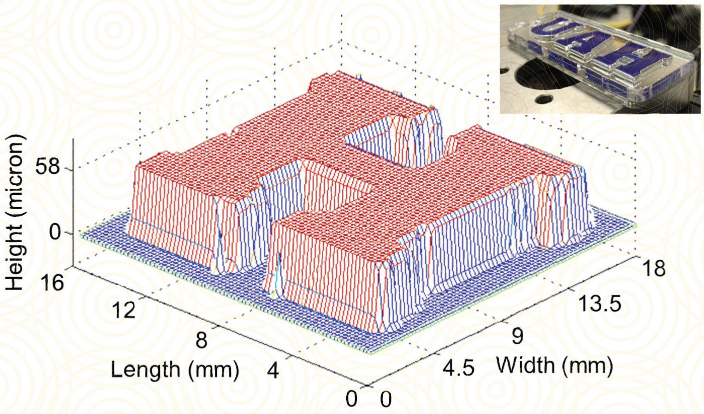
OPTICAL FREQUENCY COMB

An optical frequency comb (OFC) is an optical spectrum that consists of equally spaced spectral lines derived from the stabilisation of the pulse train generated by a mode-locked laser. This means OFCs can be used for the measurement of absolute optical frequencies. They can also be used to measure ratios of optical frequencies with extremely high precision. Applications include frequency metrology, high-precision spectroscopy, optical sensing, distance measurements, laser noise characterisation, telecommunications and fundamental physics.

quantum dots. This would undoubtedly lead to much deeper understanding of light-matter interactions at the nanoscale, with associated new applications.

Impacts have already been felt closer to home too. Not only has a new research thrust been established at UAH in precision and ultrafast dynamics in materials, but Duan's continued commitment to education and outreach has seen the creation of a number of graduate research assistantships and undergraduate summer research fellowships, as well as the Society of Optics Students club at the University. The club was launched in 2013 and promotes the growth and understanding of the importance of optics in UAH and the north Alabama region, and offers a means for undergraduate and graduate students to get involved in optics-related research and educational activities.

With such involvement in developing the next generation of optics experts, diverse research goals and impressive expertise, the PULS group will continue pushing the frontiers of optical science at the very smallest and fastest scales for years to come – inspiring others along the way.



A 3D surface profile of the letter 'H' on a University of Alabama in Huntsville key chain, obtained with the optical sampling by cavity tuning imaging system.

PRECISION ULTRAFAST LIGHT SCIENCES GROUP

OBJECTIVE

To extend the boundary of optics and photonics towards shorter time scales, higher precision, lower noise and broader scopes of scientific contexts.

KEY COLLABORATORS

Professor Richard Lieu; **Professor Seyed Sadeghi**; **Professor Robert Lindquist**, The University of Alabama in Huntsville (UAH), USA

Professor T W B Kibble, Imperial College London, UK

Professor Jinsong Nie, State Key Laboratory of Pulsed Power Laser Technology, China

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UAH Nano and Micro Devices Center (NMDC)

US Army Aviation & Missile Research Development & Engineering Center (AMRDEC)

NASA Marshall Space Flight Center (MSFC)

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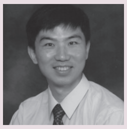

LINGZE DUAN received a BS in Physics from Tsinghua University, China, and his PhD in Electrical Engineering from the University of Maryland, College Park, USA. He joined UAH, USA, as a faculty member, in 2007, where he has been an Associate Professor since 2013. His current research interests include ultrafast nanophotonics, frequency metrology with optical frequency combs, fibre optic sensors and applications of optics in astrophysics. He was a recipient of the 2013 NSF Faculty Early Career Development Award. He is a senior member of IEEE and a member of the Optical Society of America.

PULS