The new wave in fibre optics

Enthralled by nonlinear fibre optics’ possibilities, Dr Alexandre Kudlinski leads a team that has created topographic fibres, which can be utilised in a range of technological and medical applications.

Why are you interested in optics? Can you offer an insight into your academic background?

One of the first things that interested me about optics is the possibility of performing both fundamental and applied research, especially in the field of nonlinear photonics. After earning a Master’s degree in General Physics, I completed a PhD in Photonics (about the creation of second-order nonlinearities in glasses) at the University of Lille, France, which and I defended in 2005. I was then a research officer at the University of Bath, UK, where I worked on fabrication and scientific applications of photonic crystal fibres, until I was appointed as a lecturer at the University of Lille in 2006.

How are longitudinally uniform nonlinear optical fibres limited in their capabilities?

Usually, it is desirable for optical fibres to be as uniform as possible in length, so that their guidance properties do not change longitudinally. In most applications, such as in optical communications, this is accepted to be a token of their quality. In some cases, however, there might be some benefit to changing one or several optical properties (such as mode field diameter or chromatic dispersion) over the fibre length, in order to control the properties of the guided light. This is especially pertinent in the field of nonlinear guided-wave optics.

Following on from this, can you introduce the purpose and significance of your unique and novel topographic optical fibres?

The field of nonlinear fibre optics has essentially been based on fibres with longitudinal uniformity over the last 40 years. The new kind of optical fibres that we have introduced and named ‘topographic fibres’ (which refers to the fact that fibre properties have a longitudinal ‘topographic’ variation), offer the possibility of studying nonlinear propagation effects when the guidance properties vary in a controlled way along the same direction as the optical field evolution. This new degree of freedom allows us to control fibres’ linear and nonlinear properties simultaneously – this is an actual technological breakthrough! This new class of waveguides has the potential to revolutionise several fields within and outside optics.

Do you have specific aims and objectives for the TOPWAVE project?

TOPWAVE aims to examine the opportunities topographic optical fibres bring in order to explore new directions in nonlinear fibre optics and nonlinear physics. The objective of this project is thus to provide a versatile experimental platform in which we can vary topographic fibres’ parameters in a controlled way so as to motivate new theoretical studies, perform groundbreaking experiments and stimulate new ways of thinking about nonlinear mechanisms.

Will the advent of more complex fibre topographies for light wave propagation create new technological opportunities?

To demonstrate the feasibility of fabricating topographic optical fibres with extremely accurate control of the longitudinal profile and very abrupt transitions was actually our first important technological breakthrough. Typically, we can fabricate fibres with almost arbitrary profiles, and diameter variations up to a factor of more than two over a few 10s of centimetres with good control. In terms of applications, tapered photonic crystal fibres – a simplified form of topographic fibres – have already proven their potential for white-light high-power supercontinuum sources. We are now working on a new class of ultrafast fibre-based sources using ultrashort solitons, whose properties are accurately controlled thanks to the fibre topography.

What makes topographic optical fibres ideal as an experimental platform for the further study of phenomena, such as soliton formation and modulation instability (MI)?

Soliton formation – or the creation of wave packets that have a maintained shape – and MI, which is the break-up of a stationary field into a train of short pulses, are intimately linked in optical fibres. They both rely on a balance between linear effects and nonlinear ones. Since topographic optical fibres offer an unprecedented adjustment of both linear and nonlinear properties, it is not only possible to control solitons and MI much more efficiently than in uniform fibres, but we can even explore new regimes.

Can you provide a brief summary of what you consider to be your most significant results so far from the project?

Each of the themes covered by TOPWAVE has already produced groundbreaking results, which have been published in international journals. If I have to name only one so far, I would mention the discovery of the cascaded resonant radiations mechanism linked to the destabilisation of solitons that we recently published in Optica. However, the best is yet to come.
Novel perspectives on nonlinear optics

The TOPWAVE project based at University of Lille is breaking ground in nonlinear fibre optics. Its ability to control and vary the diameter of an optical fibre will allow previously impossible studies in several fields of nonlinear physics to be conducted.

Optical fibres have become synonymous with the telecommunications industry. These thin rods of high-quality glass are crisscrossing the globe, transmitting electrical signals that contain information from computer data and telephone calls. Historically, the mark of a good optical fibre was uniformity along its length – the smoother the fibre and more consistent the diameter, the better. However, researchers from the University of Lille are challenging this paradigm with their new optical waveguides, or ‘topographic fibres’ – optical fibres whose diameter varies along the length of the fibre. They are showing that their fibres' topographies can be carefully controlled, thus enabling revolutionary studies in nonlinear physics.

A Creative Consortium

TOPWAVE – a €262,000 French National Research Agency (ANR)-funded project, headed by Dr Alexandre Kudlinski of the Laboratory of the Physics of Lasers, Atoms, and Molecules (PHLAM) at the University of Lille – is an international consortium comprised of researchers from France, Germany, Australia, the UK and Finland. The idea for the group formed from the collaborations of Kudlinski and Professor Arnaud Mussot. Between them, the duo has more than 100 publications in peer-reviewed journals and seven patent applications.

However, the expertise of the consortium does not lie solely with them, as evidenced by the team’s diverse and dynamic make-up; for example, it includes Professor Nail Akhmediev, the namesake of Akhmediev Breathers. “This is an incredibly valuable partnership,” Kudlinski enthuses. “The expertise of the collaborators cover all the relevant experimental and theoretical areas needed for this project, which allows fundamentally new results and developments that could not be obtained from each partner working individually.”

Improving All-Fibre Device Technologies

Modulation instability (MI) is an area of particular focus for TOPWAVE. This process in nonlinear physics is associated with weak perturbations in a wave, which are amplified by a strong field. In telecommunications, MI is generally considered detrimental because it creates spurious sidebands – that is, unintended signals – when information is transmitted over great distances.

The TOPWAVE consortium is investigating how topographic fibres may be able to control the MI. In this frame, the researchers are modulating the diameter of topographic fibres, examining how increasing, decreasing, oscillating and arbitrary axial profiles generates new and varied physical effects. For example, one aspect of MI they are investigating is whether fibres with optimised profiles would be able to amplify broadband signals. If so, it may be possible to create all fibre amplifying technologies for ultrashort pulses. They are also performing experiments involving pulse train generation. “We expect the pulse train to increase repetition rates and decrease pulse duration – meaning that using these topographic fibres, information could be transmitted faster,” Kudlinski expands.

Catching Breathers and Optimising Optics

Another goal of TOPWAVE is to modulate the topography of optical waveguides to control Akhmediev Breathers – periodic structures in time and localised in space, arising from stimulated modulation instability – in order to develop a generalised theory of the role topography plays in generating optical rogue waves (ORWs). These waves are giant optical pulses, which have only been discovered a few years ago. The consortium is using Akhmediev Breathers to study how to prevent or sustain ORWs, findings that could be extended to rogue waves in hydrodynamics, which occur far out at sea and are a threat to large ships. “Applications such as these illustrate topographic fibres’ ability to not only offer new perspectives in nonlinear optics, but also to experimentally investigate complex dynamics in general physics,” Kudlinski states.

The consortium is also exploring what effect MI may have in quantum optics. For instance, it is possible to generate correlated photons from quantum noise in typical optical fibres, and topographic fibres should be able to amplify this effect. The TOPWAVE researchers will combine theoretical studies with numerical simulations and experimental studies in the aim of providing a rigorous link to the dynamical Casimir effect. This will also provide a demonstration of an optimised, high-quality, fully waveguide-integrated entangled photon pair source.

Gauging a Pulse

Looking beyond MI, Kudlinski and his collaborators have set their sights on solitons – wave packets that maintain their shape along propagation. For decades, scientists have been trying to come to grips with controlling the duration, wavelength, energy and dynamics of these wave packets – a task that the TOPWAVE team aims to achieve. “We intend to gain this knowledge by flipping the problem; we will begin by first examining solitons and then, using an inverse algorithm, we will generate a topographic fibre profile,” Kudlinski states. From this, the researchers will not only be the...
Furthermore, they reported observing the results showing the emission of multiple RRs from a single soliton in a topographic fibre. These investigations led the consortium to make several discoveries concerning physical mechanisms in nonlinear physics, and they provided the first experimental results showing the emission of multiple RRs from a single soliton in a topographic fibre. Furthermore, they reported observing the generation of a polychromatic RR, which led to a RR continuum spanning over 500 nm.

Crucially, this research demonstrated that RRs do not spread out in time, but instead remain temporally localised. This finding has applications in stimulated Raman scattering microscopy, and could lead to the development of fibre-based sources capable of delivering two or more ultrashort pulses of differing wavelengths. This publication in particular highlights how Kudlinski and his collaborators are using topographic fibres to broaden their thinking about nonlinear fibre optics.

In a final publication in Optics Express, the team demonstrated that a single fundamental soliton experiencing a self-frequency shift induced by Raman scattering can emit multiple dispersive waves. In this paper, the researchers predict that further engineering of a topographic fibre will allow control of both the wavelength and emission location of dispersive waves along the fibre. In turn, this could lead to the observation of a new soliton/dispersive wave dynamics scenario.

**MAKING WAVES IN THE SCIENTIFIC COMMUNITY**

The TOPWAVE group has already published several results from their research. In a letter published in Optics Letters this August entitled ‘Experimental dynamics of Akhmediev Breathers in a dispersion varying optical fibre’, the team reported findings that the evolution of these structures in the presence of varying dispersion (topographic fibres) can be quasi-stabilised in space at their point of maximal compression. These results may have implications on better predicting how waves propagate in deep water.

Another article, published in Optica in October, reported the scientists’ investigations into cascaded resonant radiations (RRs) emitted by solitons. Cascades of RRs are caused when an RR is temporally recompressed due to the varying geometry of the fibre. These investigations led the consortium to make several discoveries concerning physical mechanisms in nonlinear physics, and they provided the first experimental results showing the emission of multiple RRs from a single soliton in a topographic fibre. Furthermore, they reported observing the generation of a polychromatic RR, which led to a RR continuum spanning over 500 nm.

Crucially, this research demonstrated that RRs do not spread out in time, but instead remain temporally localised. This finding has applications in stimulated Raman scattering microscopy, and could lead to the development of fibre-based sources capable of delivering two or more ultrashort pulses of differing wavelengths. This publication in particular highlights how Kudlinski and his collaborators are using topographic fibres to broaden their thinking about nonlinear fibre optics.

In a final publication in Optics Express, the team demonstrated that a single fundamental soliton experiencing a self-frequency shift induced by Raman scattering can emit multiple dispersive waves. In this paper, the researchers predict that further engineering of a topographic fibre will allow control of both the wavelength and emission location of dispersive waves along the fibre. In turn, this could lead to the observation of a new soliton/dispersive wave dynamics scenario.

**ONWARDS AND UPWARDS**

Kudlinski and his team have great confidence in their ability to use their new optical fibre waveguides to further elucidate the properties of MI, solitons, Akhmediev Breathers and even quantum entanglement. “On a short-term basis, we are quite confident we will succeed in completing all the demonstrations and proof of principles of new physical mechanisms we planned for the TOPWAVE project; however, on a long-term basis, I do not know where this will really take us, and this is the beauty of research,” Kudlinski concludes.