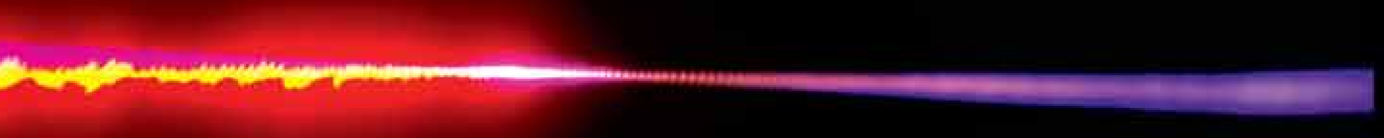


Far from falling (ultra)short

With applications across scientific fields, **Dr Stelios Tzortzakis** details some of the unique properties that led his team to study ultrashort nonlinear laser propagation phenomena

Can you provide an overview of your research and principal goals?

Our research involves intense ultrashort laser pulses, whose intensity allows the study of highly nonlinear phenomena. More specifically we work on two major axes, the study of nonlinear propagation phenomena (filamentation) and the development of novel secondary radiation sources across the electromagnetic spectrum with special emphasis on terahertz (THz) radiation. Our work involves both fundamental physics studies as well as applications which span interdisciplinary ground, involving photonics, materials, cultural heritage and biochemistry. Finally, tailoring the strong nonlinearities to control the propagation properties of the intense laser beams is of major importance and we are strongly involved in this problem.

Can you give an insight into your group's studies involving filamentation? How are you seeking to advance studies within this area, and can you highlight how light filaments are used in real-life applications?

Filamentation is a major research field for us. Our focus here is related to ways one may control the properties of self-guided laser beams, and thereby obtain tailored filaments. Balancing strong nonlinearities is not a trivial task: in our work we explore different schemes to approach the problem. For instance, a research line we have introduced involves the use of photonic lattices, while another involves the combination of non-diffracting beams like Bessel and Airy beams. Tailoring means that we have control on the filaments' length, uniformity and peak intensity. This control has strong implications in applications like the generation of very intense THz pulses, or the generation of higher harmonics and attosecond pulses.

What would the possibility of creating more sophisticated 3D plasma photonic lattices open up in terms of controlling the propagation of high-intensity ultrafast laser beams and laser filaments?

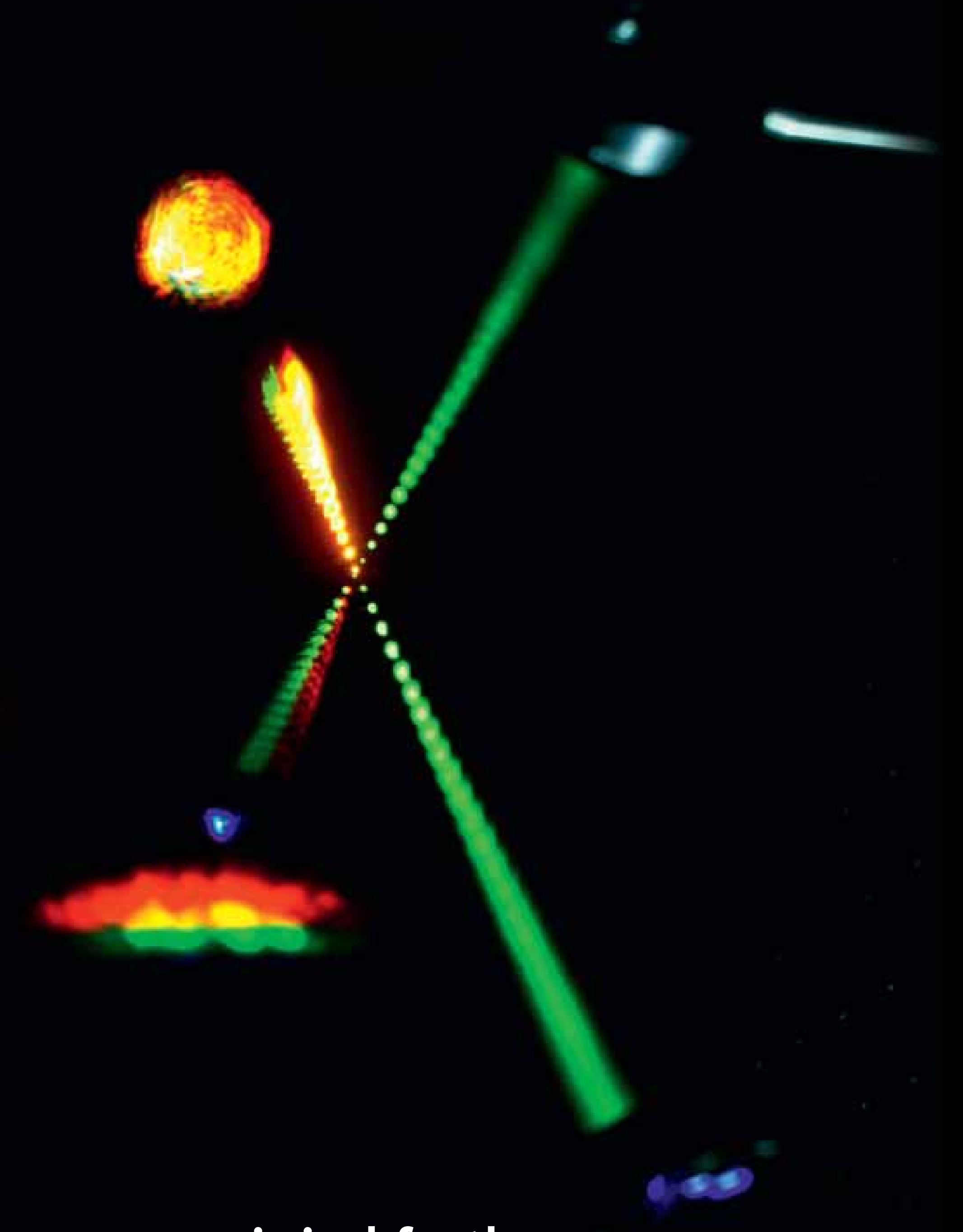
Following the previous question, one of the ways we have introduced in the control of filamentation is the use of photonic lattices. These lattices can be 2D or 3D and we have shown that by adjusting the parameters of the lattice, one can obtain efficient control of the filament properties. Practically, the lattices can be permanently written waveguide arrays in the bulk of glasses, yet for filaments in gases, things are much more complicated since the intensities there are so high that all optical elements placed in the path of the filaments would be permanently damaged. Thus, we have introduced the idea of using 'virtual' lattices– like, for instance, plasma lattices. Such lattices are temporary since they have a short lifespan, yet can withstand the high laser intensities.

Metamaterials have experienced increasing interest due to the electromagnetic properties they exhibit, such as negative refraction, diffraction-limit breathing imaging and cloaking. How would you define metamaterials, and how might their properties be considered useful in terms of future application?

Metamaterials are special since their intriguing electromagnetic properties are difficult or impossible to obtain from natural materials. Over the course of the last 10 years, this field of research has experienced exponential growth. Interestingly, the emergence of metamaterials science coincides with the intense emerging interest in terahertz radiation (THz), for which efficient forms of electromagnetic manipulation are sought. Considerable efforts are being made from both scientific disciplines (metamaterials and THz science) to fabricate and characterise various metamaterial components (waveplates, filters, amplifiers, switches, etc.) which could efficiently control the THz radiation properties.

Finally, would you like to add any further comments on your research?

The future of this research field looks as bright as the intense sources we use and develop. Of particular interest beyond the basic physics studies we are conducting are the applications, especially in materials and biology sciences. The new intense THz sources we are working on may prove valuable in understanding biological actions, or even gaining control over them.



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ULTRASHORT NONLINEAR LASER INTERACTIONS AND SOURCES GROUP

MULTIRAD

ENERGETIC ULTRA-FAST LASER-DRIVEN RADIATION SOURCES: APPLICATIONS IN BIOLOGY, CHEMISTRY AND PHYSICS

FORTH Institute of Electronic Structure and Laser

Waves of wonder

Harnessing ultrafast lasers in the Terahertz range of the spectrum, the FP-6 funded **MULTIRAD** study has broad-ranging applications, from metamaterials to masterpieces


A LASER FILAMENT IN ATMOSPHERE

SINCE THE 1950s, lasers have harnessed broad applications in fields ranging across military, scientific, medical, industrial and commercial fields. In this continued multi-sectoral development, MULTIRAD is developing energetic, ultrafast, laser-driven radiation sources, with applications across scientific boundaries. Using a powerful and high-repetition rate infra-red laser, secondary sources of radiation from x-rays, UV and visible waves, through to far infrared, Terahertz and microwaves, are produced. This laser fires in a femtosecond (fs): one quadrillionth, or one millionth of one billionth, of a second. This astonishing brevity is part of the appeal of these secondary sources which stem from the laser pulse passing through matter such as solids, gases or plasmas, resulting in highly non-linear processes.

With an internationally recognised track record in this field, Dr Stelios Tzortzakis is leading the UNIS team at IESL-FORTH, Greece, in its aims to characterise the attributes of these secondary sources – spectral and spatio-temporal – and discover how they might be applied in photonics, biomedicine, chemistry, materials science and physics. Through a prestigious Marie Curie Excellence Grant, Tzortzakis has set his lab and team in developing various applications like: ultrashort electron bunches to study proteins and other biological agents, THz radiation in biomedical imaging, and micro structuring and engraving of photonic elements and dynamical metamaterials.

A major facet of the group's research is filamentation: dynamically self-trapped laser beams that propagate in all transparent media with a very narrow width and high intensity[1,2]. Because of their unique attributes, a number of applications have been suggested; however, their development hinges upon overcoming the dynamic spatio-temporal evolution of filamentation, to tailor intensity, diameter, length and induced electron density. Diffraction-free Bessel or Airy beams can lead to stationary filaments and uniform plasma strings[3]. The self-healing characteristics of Airy beams render them able to reconstruct their profile when partially blocked during propagation, while their transverse bending could be exploited when optical power has to be delivered to a destination in a bended trajectory beyond an obstacle[4].

ON TERAHERTZ

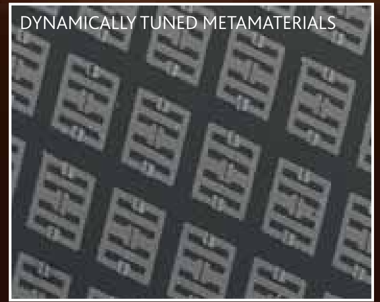
Terahertz (THz) have distinctive qualities that make them particularly useful in generating functional forms of radiation. Their long wavelength makes them less prone to Mie scattering, caused when particles through which the light passes are larger than the light wavelength. This means that many insulating materials such as cloth, paper, wood, plastic and dry dielectrics (insulators) are transparent to THz radiation. Due to their low photon energy, the waves do not ionise biological tissue, and are strongly absorbed by water, preventing the radiation penetrating the human body. THz therefore has exciting potential as a tool for nondestructive screening and imaging, from living humans to ancient paintings[5]. THz pulses can be detected coherently through sampling their electric field and could prove an excellent tool for characterising the absorption and dispersion of many materials. Within the THz range lie many solid state phenomena – such as band gaps of superconductors, phonon models of most semiconductors and crystals – so this form of radiation could help elucidate these[6].

A FRONTIER IN BIOCHEMISTRY

The 'grand challenge' for both chemistry and biology, as Tzortzakis puts it, is control of chemical reactions in a highly specific manner – something biological systems do far better than chemists. The THz region of the spectrum represents the final repository of vibrational energy in a molecular system. In cells, these can be the vibrational modes localised in groups of amino acids which occur in femtoseconds or even less, which might be considered 'chemical'; they can also be structural dynamics occurring in nano- to milli-seconds, which could be considered 'biological'. The use of THz radiation could allow tracking and imaging of the complex molecular interactions within a single cell and therefore represent a real frontier for biochemistry.

PHOTONIC CIRCUITS AND METAMATERIALS

As in electronic systems, photons can be used to manipulate information through transporting, leading, amplifying and storing light. With fibre-optics now widely used to transport light over long distances, ultrashort intense lasers could prove efficient tools in fabricating photonic micro- or nano-structures also. In optical technologies, the properties of materials such as glass can be modified to optimise how they interact with the light. Ultrashort intense lasers could enable much more defined and complex alterations to control light properties. Not only this, but in some conditions filamentation leads to self-organised nano-structures, which could be used as components in nanophotonics devices.


DYNAMICALLY TUNED METAMATERIALS

Metamaterials – or periodically arranged artificial structures – have garnered much interest over the last decade due to their electromagnetic properties, which include negative refraction, diffraction-limit breathing properties and cloaking. These properties, which are extremely difficult to reproduce in natural materials, sit well alongside THz science, as both the metamaterials and THz disciplines seek to fabricate and characterise components to efficiently control THz properties. Interestingly, metamaterials act as dynamical switches for THz radiation, judiciously incorporating photosensitive semiconductors in their designs[7-8].

THE BIGGER PICTURE

Developing THz pulses with tailored properties could have specific applications for restoring, investigating or maintaining cultural heritage[5]. As Tzortzakis explains, pulse qualities such as intensity, duration, spectral bandwidth and, most notably, polarisation could make them ideal for investigating sensitive or ancient cultural artifacts such as paintings: "In spectroscopic and imaging applications, we have two advantages over classical techniques: the large spectral bandwidth and the intensity of the radiation that allows us to look into highly absorbing media," he remarks. After initial work in spectroscopic analysis of various components, Tzortzakis explains how the technology is evolving: "The field is now moving towards imaging of hidden layers and observations of hidden defects. The main limitation in THz imaging remains the acquisition time and the low power of the sources".

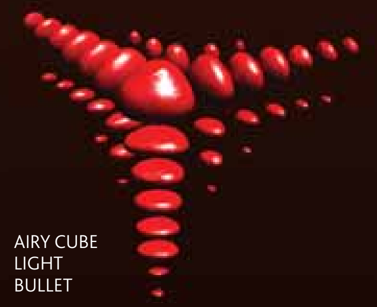

THZ IMAGING COULD UNCOVER HIDDEN INFORMATION IN VALUABLE ARTEFACTS

In another technique called Laser-Induced Breakdown Spectroscopy (LIBS), where traditionally a laser beam is focused on a target to obtain high enough energy density to ablate them, Tzortzakis believes that filaments could make significant advances. Using femtosecond laser filaments, extremely high light intensities can be delivered to remote sites, causing breakdown of solid targets, vapour or aerosol molecules, enabling studies of their composition[9]. In environmental sciences, this could be useful in generating plasma emission far from the laser source.

AIRY LIGHT BULLETS

With such a panoply of theoretical and practical applications, Tzortzakis's team is far from resting on its laurels. As he outlines, their discoveries in nonlinear propagation of intense femtosecond lasers are ongoing: "We recently demonstrated the existence of spatio-temporal Airy light bullets in the linear and nonlinear regime[10]. These non-spreading wavepackets can find applications in telecoms and biology". As regards secondary sources, they have demonstrated means of obtaining tunable intense THz pulses, as well as an 'elegant' means of controlling the radiation's polarity[11-13].


PHOTONIC CIRCUITS VS. ELECTRONICS


AIRY CUBE LIGHT BULLET

Tzortzakis is in no doubt that the interdisciplinary makeup of their team has been pivotal to their successes: "Today the problems we are working on are so complex they require the cooperation of specialists from different disciplines. For instance, in addressing many biological problems one may have to combine knowledge and competencies, beyond biology, from fields like physics, chemistry, mathematics, informatics, and others". Finally, the institute's association with Laserlab Europe – a unique network of European national laser laboratories – has provided access to both the best research talent and state-of-the-art infrastructures. Tzortzakis is in no doubt as to the importance of Laserlab and the cooperation enjoyed with other research institutes on the continent: "Numerous collaborations have been established with researchers across Europe and from different disciplines, while joint research activities are enabling further improvement of our facilities," he concludes.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MULTIRAD

ENERGETIC ULTRA-FAST LASER-DRIVEN RADIATION SOURCES: APPLICATIONS IN BIOLOGY, CHEMISTRY AND PHYSICS

OBJECTIVES

MULTIRAD's main idea is the establishment of a unique facility gathering secondary ultrashort intense laser sources spanning the electromagnetic spectrum. Many of these sources are based on nonlinear propagation phenomena, where filamentation tailoring allows unique tunability. The applications of the project are of a wide, interdisciplinary nature.

FUNDING

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DR STELIOS TZORTZAKIS received his PhD from the Ecole Polytechnique in France (2001). He has worked in many research laboratories in France and Greece, and since 2003 he has held a CNRS position at the Ecole Polytechnique. He is the recipient of a Marie Curie Excellence Grant, with which he has founded and now leads the UNIS group at IESL-FORTH in Greece, where he is also a Principal Researcher. He is a recognised expert in nonlinear laser propagation phenomena and has created the *filamentation.org* website, a unique information resource for the related scientific community.