SCIENTIFIC APPS

Fourier transform on the move

It is now possible to calculate the Fourier transform of an image on your smartphone, thanks to a new app developed by two nanophotonics researchers in The Netherlands. "2D-Fourier" is available for free on the Apple store and runs on both the iPhone and the iPad. Versions for additional platforms may become available later.

The Fourier transform is a well-known mathematical tool that allows physical phenomena to be analysed in the inverse domain — a technique used throughout many areas of scientific research. As humans we are familiar with the concepts of hearing and seeing, whereby we 'measure' sound as a function of time and observe space in spatial coordinates. Many physical phenomena, however, are best analysed and understood in the inverse domain, where they are visualized in a world of reciprocal units. For example, in photonics, the Fourier transform links an optical pulse's temporal and spectral characteristics, makes it possible to analyse an image in terms of a distribution of spatial frequencies, and has inspired the field of Fourier optics and focal plane information processing.

Albert Polman, director of the FOM Institute AMOLF in Amsterdam, together with his PhD student Ernst Jan Vesseur, wanted to provide scientists with a means of calculating Fourier transforms on a mobile platform. The app is intended to provide a basic insight into the Fourier transform, rather than for use as a research tool. The user first takes



a picture using the device's camera, after which the Fourier transform of this image is automatically shown on the screen. This gives direct insight into the distribution of two-dimensional spatial frequencies from which the image is composed. As a second feature, the user can draw over the original or Fourier-transformed image to explore what effect this has on the corresponding Fourier-transformed/original image. This provides additional insight into what spatial frequencies represent what part of the image.

The tool is meant for master students, PhD students and researchers who are

learning about the Fourier transform in fields such as nanophotonics, photovoltaics or any other areas of physics that involve transforms between time and frequency, or between space and spatial frequency.

"The Fourier transform is complex, partly because the human brain has problems understanding the inverse of space and time," explained Polman. "This tool may help students to gain an insight into the Fourier transform, and also directly helps us in our nanophotonics research."

OLIVER GRAYDON

NONLINEAR OPTICS

Three-in-one microscopy

Using extremely broadband ultrafast near-infrared pulses, scientists have demonstrated simultaneous secondharmonic-generation, third-harmonic-generation and four-wave-mixing microscopy, enabling a range of different structures and functional groups in a biological sample to be imaged at once.

Brett Pearson and Thomas Weinacht

ver the past two decades, nonlinear optical techniques have transformed laser-based biological microscopy by introducing multiphoton excitation, which allows for increased depth penetration, three-dimensional localized excitation

and reduced photodamage¹. The most prevalent experiments have been based on two-photon fluorescence microscopy, which involves exciting a molecule to a higher-lying state by the simultaneous absorption of two photons from a laser beam. The high intensities required for two-photon excitation necessitate the use of short-pulse lasers as the light source, with typical pulse durations of less than 10^{-12} s (known as 'ultrafast' pulses). As in traditional microscopy, an image is formed by collecting fluorescence from the excited state while the sample and light source are scanned relative to each other. A host of other nonlinear effects are possible in addition to two-photon fluorescence, including processes that do not require the use of fluorescent samples — techniques known as 'label-free imaging'.

In their recent report², Romedi Selm *et al.* simultaneously collect light from three different multiphoton interactions, namely second-harmonic generation (SHG), third-harmonic generation (THG) and four-wave mixing (FWM), to provide an unparalleled view of biological samples.

The terms SHG, THG and FWM refer to the different nonlinear optical processes that occur in a molecule in response to the strong electric field present in an intense ultrafast laser pulse. For conventional light sources such as a lamp or the Sun, the oscillating electric field is relatively weak and the displacement of atomic and molecular electrons driven by the corresponding Lorentz force is quite small. The restoring force is approximately linear with displacement and the motion is that of a simple harmonic oscillator, such as a mass on a spring or a pendulum oscillating after a small displacement. However, the much larger electric fields of an ultrafast laser pulse cause the electrons in a molecule to undergo large displacements from equilibrium and therefore experience a nonlinear restoring force; the peak light intensity in a multiphoton microscope focus is typically twelve orders of magnitude larger than the intensity of sunlight on the Earth. The response of the material to the applied light becomes a nonlinear function of the laser driving field, and the oscillating electrons radiate at new frequencies³. For instance, if the material response contains a quadratic dependence on the driving field strength, the spectrum of the emitted radiation will contain the second harmonic of the laser — SHG.

The dominant response depends on the frequency of the driving laser and the structure of the molecules in the laser field. For example, significant SHG does not occur when the restoring force is completely symmetric (that is, when the restoring force on an electron is the same for the field pointing in either direction). Instead, SHG tends to come from boundary regions or locations in a cell where the symmetry is broken by an interface. THG is also particularly sensitive to boundaries, and although both SHG and THG tend to originate from interfaces, they are typically enhanced for different molecules and structures due to resonant contributions at different frequencies. In contrast with



Figure 1 | Strutural information of *Caemorhabditis elegans* can be extracted by simultaneous SHG, THG and FWM imaging modes at a microscope focus. SC, supercontinuum pulse.

SHG and THG, FWM results in a signal that is efficiently generated in bulk⁴. FWM therefore serves as a nice complement to SHG and THG, which preferentially image boundary regions.

Because different nonlinear processes are sensitive to distinct molecules or structures in a cell, performing multiple forms of microscopy can provide a more comprehensive view than exploiting these techniques individually. Selm et al. simultaneously collect light generated through SHG, THG and FWM, thus allowing them to construct a detailed map of the cell without worrying about registration problems or dynamic changes in the cell between scans of different modalities. These various signals are enhanced near resonance, which implies that broad-bandwidth pulses provide access to more potential resonances than narrowbandwidth pulses, provided that all the frequency components arrive at the same time. Because a short pulse in time requires a large frequency bandwidth (time and bandwidth are Fourier-transform pairs), it is beneficial to deliver as short an optical pulse as possible to the sample.

Selm *et al.* use a 1,550 nm femtosecond fibre laser with a repetition rate of 40 MHz and a 3-mm-long nonlinear optical fibre to generate ultrabroadband pulses centred in the near infrared². Because the various

frequency components in the pulse travel at different group velocities, the propagation of a short pulse through a dispersive material such as glass can result in significant broadening of the pulse in time, and ensuring the pulse duration remains short at the sample presents a significant challenge. Active dispersion control is typically required to ensure that the frequency components making up the pulse are properly phased. For ultrabroadband pulses travelling through a thick optical component such as a microscope objective, dispersion control often requires the use of a complex optical arrangement such as an optical pulse shaper⁵. Instead of a pulse shaper, Selm et al. make use of a split-prism compressor to efficiently compress and deliver a two-cycle, bandwidth-limited pulse (with duration of less than 8 fs) to the sample position². The split-prism compressor is much simpler than an ultrafast pulse shaper and more effective than a traditional singleprism pair compressor. The simplicity and effectiveness of this technique are promising for widespread use in multiphoton microscopy.

Figure 1 depicts SHG, THG and FWM imaging based on the approach of Selm *et al.* on a sample of *Caemorhabditis elegans* positioned at a microscope focus. For clarity, the different signals are shown to originate from separate spatial locations, but in reality all signals can come from any location in the cell. As seen in the energy level diagrams, the SHG signal is enhanced when the energy of two photons in the laser field is similar to the separation between the two electronic states of the molecule. Similarly, THG is enhanced when three photons of the laser field are equal to the energy difference between states. Exploiting resonances is a general property of nonlinear interactions³, and it also holds true for FWM. As shown in Fig. 1, independent recording of the three signals is aided by the fact that they are spectrally distinct and can therefore be separately measured using a spectrally resolved detector or dichroic mirrors and colour filters.

The apparatus described by Selm *et al.* provides high-quality images capable of discriminating between different materials by simultaneously recording signals from multiple nonlinear microscopy techniques. The simplicity, stability and effectiveness of the device ensure that it will be attractive for widespread use in biological and biochemical imaging.

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ACOUSTICS

Fibre-optic pickup

Guitars and violins may soon sound better than ever thanks to photonic technology. Researchers in Italy and Canada have developed a fibre-optic pickup that is capable of converting acoustic vibrations from a musical instrument to an electronic signal with a claimed distortion-free dynamic range of 50 dB for frequencies ranging from 8 Hz to 30 kHz (*Opt. Express* **19**, 25057–25065; 2011).

Saverio Avino and co-workers from Istituto Nazionale di Ottica in Italy and Queen's University and Ryerson University in Canada say that their photonic pickup is compact, lightweight and can be easily attached to vintage musical instruments. They also say that their device reproduces lower frequencies more accurately than conventional piezoelectric pickups, thereby providing a broader acoustic bandwidth and producing a more natural sound.

The pickup is based on a fibre Fabry-Pérot cavity comprising two high-quality (transmission extinction ratio of 23 dB) fibre Bragg gratings spaced 2 cm apart. The cavity can be used as an acoustic transducer because its length — and therefore the spectral position of its transmission fringes — changes with the applied strain.

Piezoelectric-based pickups have traditionally been used for amplifying or recording musical instruments, but they have a limited acoustic response. Although fibre-optic pickups have a greater frequency response than piezoelectric pickups, they have previously suffered from absorption losses and optical noise arising from uncontrollable fluctuations in the laser emission and



detector response. Avino and co-workers have now overcome these problems by adopting an interrogation method that locks the frequency of the probe laser tightly to the audio-modulated reflections.

The transmission fringes of the Fabry-Pérot cavity had a narrow linewidth of around 25 MHz, which was essential for locking the distributed feedback laser and for detecting small strain modulations. The researchers attached the cavity to the guitar body and locked the distributed feedback laser, with a linewidth of 5 MHz at 1,549 nm, to the peak of a cavity fringe using Pound-Drever-Hall laser stabilization — a wellknown technique for demanding tasks such as the interferometric detection of gravity waves. They extracted the error signal from the reflected cavity field by mixing the detector signal with the modulation signal applied to the laser. They then fed the error signal to a proportional-integral servo amplifier whose output was fed back to the distributed feedback laser current.

The researchers say that their fibreoptic pickup system is largely immune to optical noise sources. They captured distortion-free audio recordings of guitars with a frequency response from the infrasound (around 8 Hz) to 30 kHz, with a 50 dB dynamic range in acoustic power. It should be noted that the upper limit of the acoustic frequency range (30 kHz) was determined by the speed of the servo loop — not by the cavity finesse — and that further improvements in dynamic range and frequency response may therefore be possible.

The cost and complexity of the photonic pickup system must be reduced before it can be adopted by guitar manufacturers and musicians, but Avino and co-workers are confident that this can be achieved.

"All components are off-the-shelf electronic and optical parts, and the laser driver can be easily replaced by a home-built current source," comment the authors in their paper. "We estimate that a dedicated sensor system may be built from components costing US\$1,000 or less. This is comparable to the cost of a studio-quality ribbon microphone."

The photonic guitar is current being exhibited at the Canada Science and Technology Museum in Ottawa until April 2012.

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