semiconductors such as GaAs and AlGaAs, charge carriers rapidly transfer out of the lowest conduction band to reside in higher-energy states before gaining sufficient energy to impact ionize, and the advantage of the conduction-band discontinuity is lost.

In view of the numerous experimental and theoretical reports that have previously heralded a solid-state PMT, it is worth asking how plausible the results and interpretation reported by Ren and colleagues are. There are certainly grounds to be optimistic. It is known that large conduction-band offsets can exist between two dissimilar materials. Work undertaken by several groups (including at the University of Sheffield) has shown that in narrow-bandgap semiconductor materials such as HgCdTe and InAs, only electrons seem to ionize and they do this at very low threshold energies. It is thus easy to understand why a better performance could be obtained by the structure shown in Fig. 1b that tends to spatially localize the ionization process in the narrow-bandgap material. In short, this photocurrent enhancement mechanism is entirely feasible.

However, the technological challenges that must be overcome before realizing a true solid-state PMT must not be underestimated. Although a doubling of the photocurrent is certainly valuable, to achieve true PMT-like performance will require multiple repeats of this AlInAsSb/InAsSb staircase heterojunction (Ren and colleagues' work reports just a single-step staircase) within the APD (necessitating the application of high voltages). In addition, the fine details of the multiple interfaces have to be controlled precisely and finally the background doping throughout the structure will need to be controlled very accurately. Another fundamental issue is that the dark currents in these narrow-bandgap materials can be large at room temperature and devices will need cooling to reduce this to acceptable levels. Despite these obvious problems, it does finally look like that the performance of semiconductor APDs can be substantially improved to start to mimic the behaviour of a classical PMT. As is often the case, it is likely to be the financial investment needed rather than fundamental problems with the device physics that may preclude the appearance of a semiconductor-based PMT in the near future. ❐

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OPTOMECHANICS

Vibrations copying optical chaos

Mechanical oscillation in a microtoroidal optical cavity transfers chaos from a pump to a probe laser beam with a different wavelength. Through stochastic resonance, the combination of noise and internal chaotic dynamics leads to amplification of optomechanically induced light self-oscillations.

Marc Sciamanna

The interaction between a light wave and the mechanical vibration of a macroscopic object — the study of which is known as optomechanics — results in a low-dimensional system showing nonlinear dynamics[1]. In a standard optomechanical set-up, the radiation pressure of photons on the mirrors forming an optical cavity causes the mirrors to move, thus exciting a mechanical vibration mode (Fig. 1). The mechanical motion, in turn, modifies the detuning of the incoming laser beam with the optical cavity resonance, hence altering the circulating beam. The dynamics of the field phase and amplitude inside the optical cavity are then nonlinearly coupled to the dynamics of the mirror position — the radiation pressure force being proportional to the field intensity. As has been popularized by Lorenz in the study of the so-called butterfly effect[2], any autonomous nonlinear system with at least three coupled state variables is a candidate for manifesting chaos, that is, unpredictable dynamics, the root of which is the deterministic sensitivity to the initial conditions.

In an optomechanical set-up (zoom-in on the optomechanical interaction in Fig. 1), it is known that a light beam that is blue-detuned with respect to the cavity resonance will release its energy to phonons at the frequency of the mechanical mode[3]. The light beam, therefore, self-amplifies the mechanical oscillations up to a point where the optomechanical oscillation overcomes the mechanical damping, hence resulting in an optomechanical oscillator. The transmitted light intensity is self-modulated at the frequency of the mechanical mode. When the intensity of the incoming light is further increased, the self-sustained oscillation bifurcates to more complex nonlinear dynamics including chaos[4].

Chaos is ubiquitous in nonlinear optical cavities, either resulting from nonlinear light–matter interaction[5,6] or from the nonlinear coupling between optical modes such as in laser cavities[7]. What makes optomechanical chaos peculiar, however, is the fact that the chaos is structural. Indeed, the self-oscillation frequency and chaos bandwidth can be adjusted by engineering the optical cavity and, more specifically, by engineering its corresponding mechanical and optical quality factors. Scalability and integrability of a large number of such optomechanical oscillators is therefore within reach for investigation of complex collective phenomena[8].

Writing in *Nature Photonics*, Faraz Monifi *et al.* report[9] that a single optomechanical oscillator can drive the transfer of optical chaos from a pump beam at one wavelength (1,550 nm) to another weaker probe beam at a different wavelength (980 nm). The physics, in brief, is the coupling of optical modes to the same mechanical mode in a microscopic toroidal optical cavity.

As shown in Fig. 1, two beams are coupled into and out of a microtoroidal resonator through a tapered optical fibre. The first beam (pump) is from an external cavity laser with a central wavelength of 1,550 nm and its power is increased to overcome the threshold for the onset of mechanical oscillations. The second beam (probe) is also from an external cavity laser but its central wavelength of 980 nm is largely detuned from the pump beam such that there is no direct crosstalk between the optical fields. In addition, this probe beam is intentionally kept at low power, well below the threshold for the onset of optomechanical self-oscillation. When the pump power is increased, the same sequence of period-doubling bifurcations to chaos is observed in both the transmitted pump and probe beams. In other words, the light intensities in both pump and probe beams start self-oscillating at the frequency of the mechanical mode (around 26 MHz) but with new frequency components at one half, one fourth, and one eighth of that frequency and with higher harmonics up to a broadband chaotic spectrum encompassing many frequencies as the pump power increases. Taking into account the dynamics of two optical modes with different cavity detunings but coupled to the same mechanical mode, the theory confirms that the pump and probe beams share the same frequency content in their power spectral densities (see the experimentally recorded chaotic power spectra in Fig. 1). Although differing in the details, the transfer of dynamics from one optical field to another reminds us of the first Huygens synchronization experiment[10] in which two pendulum clocks hanging from a common beam show the same oscillatory motions thanks to imperceptible forces they exert on their connecting beam. It is worth noting, however, that the coupling demonstrated in Monifi and colleagues' experiment concerns two oscillators with the same central frequency that is determined by the mechanical mode of the microtoroidal cavity, although the two injected optical beams have different optical frequencies. The different cavity detunings of the pump and probe beams only have an impact on how strongly both beams couple to the mechanical mode and therefore on how reliably the pump beam dynamics replicate into the probe beam dynamics.

As mentioned earlier, the resonance frequency of probe or pump beam modulation is pinned by the frequency of the mechanical vibrations and is therefore independent of the pump intensity. Still, when measuring the signal-to-noise ratio (SNR) of the resonant peak versus the pump power, a resonance phenomenon is observed: a specific value of the pump power leads to an optimal SNR (Fig. 2). Interestingly, the range of pump power in which resonance occurs is also the parameter range in which chaotic dynamics is found in both pump and probe beams. This has been confirmed by the computation of a positive maximum Lyapunov exponent showing the divergence of nearby trajectories in the pump and probe beam dynamics. Increasing the pump intensity leads to an increasing noise level due to the increasing bandwidth of the optomechanical back-coupling. Still, and in contrast to the common belief, the SNR is not a monotonous decreasing function of the increasing noise — the system enhances its optical response to the mechanical oscillations for a given pump power in spite of the noise increase. This phenomenon shows the signature of so-called stochastic resonance[11], which is common in nonlinear systems. Initially suggested to explain the periodic recurrence of ice ages, stochastic resonance is related to the optimal response of a nonlinear bistable system to a weak modulation in the presence of noise

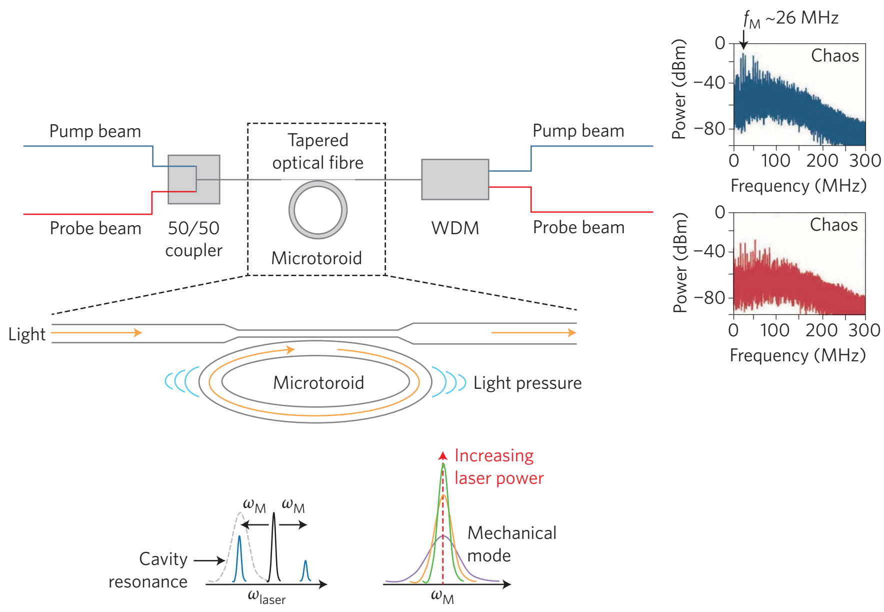

Figure 1 | Transfer of optical chaos from pump to probe laser beam through nonlinear interactions with a mechanical mode. Top: Transfer of optical chaos from a pump (blue) to a probe (red) light beam as a result of optomechanical interaction with a mechanical mode in a microtoroidal resonator. WDM, wavelength-division multiplexer. Bottom: The optomechanical dynamic back-coupling in the case of a blue-detuned laser beam (with respect to the cavity resonance frequency). ω_{laser} is the optical frequency of the pump laser beam. Side bands appear due to mechanical vibrations (at frequency ω_M) with a preference for the Stokes component due to cavity enhancement. The released energy is transferred to phonons, hence amplifying the mechanical mode when increasing the light power up to a situation where the gain overcomes cavity losses resulting in sustained mechanical and optical self-oscillations at frequency ω_M. Top right: When the pump laser intensity is further increased, the transmitted pump laser spectrum (blue) becomes chaotic with a broadband spectrum that extends beyond the self-oscillation frequency f_M. The probe laser spectrum (red) reproduces the chaotic features of the pump laser spectrum.

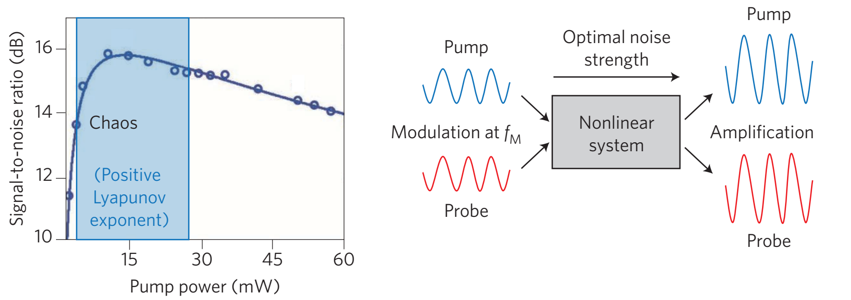

Figure 2 | Stochastic resonance in an optomechanical system. Stochastic resonance manifests itself as an optimal signal-to-noise ratio of the pump or probe resonance peak in the power spectrum when the pump power is increased (left). A schematic view (right) summarizes the stochastic resonance phenomenon with amplification of the initially weak modulation in both pump and probe light intensities. Left panel adapted from ref. 9, Nature Publishing Group.

(Fig. 2). The increasing noise leads to an adjustment of the switching time between the bistable states to the modulation period. In the work of Monifi *et al.*, when the pump power is increased, the system enters into a nonlinear dynamical regime where switching possibly occurs between several chaotic attractors, thus realizing the multi-stability condition towards the observation of stochastic resonance[12].

This work demonstrates how the interplay between nonlinear science and nonlinear optics can improve both device functionalities and performances. Although chaos, by definition, is unpredictable dynamics, it is remarkable to realize that different but connected oscillators can copy–paste their chaotic properties. Chaos broadcasting is a well-known property of optically coupled chaotic oscillators and has been analysed in the context of chaos synchronization and chaos-based communications[13]. It is also demonstrated by Monifi *et al.* for optical oscillators that are 'mechanically' coupled. Systems based on coupled optomechanical oscillators have much to bring to chaos-based applications and to the physics of collective behaviours of a large number of coupled nonlinear oscillators. Although this field was initially developed with coupled lasers or hybrid optoelectronic oscillators, the ease of integration, scalability and engineering of the nonlinearity in optomechanical systems makes them good candidates for further studies including the investigation of chaotic properties at the quantum level. However, most of the experimental studies related to optomechanical oscillators and chaos remain confined to a small number of coupled modes[8] and at relatively low frequencies (here MHz, but GHz oscillations have been demonstrated[14]). Chaos of low dimension and with limited bandwidth is considered a drawback for implementing chaos-based secure data communication at high bit rates[13]. In the light of recent works[15], application of optomechanical chaos to a physical source of entropy at a high bit rate seems, however, feasible. The sensitivity of the chaotic dynamics to slight changes in the incoming light power or frequency also makes these devices interesting for chaos-based sensing applications. ❐

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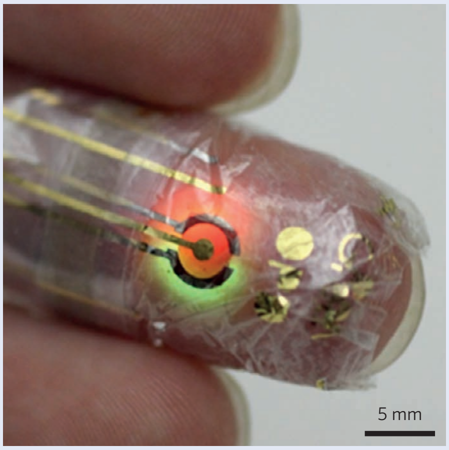
OPTICAL SENSORS

Ultraflexible on-skin oximeter

An organic pulse oximeter that can be laminated onto a fingertip to determine the concentration of oxygen in the blood has recently been developed by researchers in Japan (*Sci. Adv.* **2,** e1501856; 2016).

The sensor, built by Tomoyuki Yokota and co-workers from the University of Tokyo, comprises two organic polymer light-emitting diodes (PLEDs), operating at 517 nm (green) and 609 nm (red) respectively, shaped as semi-circles that enclose an organic photodetector (OPD; pictured).



AAAS

The PLEDs and the OPD each have a thickness of 3 µm, which is one order of magnitude thinner than human epidermis. The light-emitting diodes and the photodetector are manufactured on an organic Parylene substrate and are protected by an organic–inorganic passivation layer. Indeed, the latter ensures that the PLEDs and OPD do not deteriorate in air. For example, the authors observe that the passivation layer extends the operational half-life of the PLEDs from 2 to 29 h. Additionally, the thinness of the individual components ensures mechanical flexibility, with the PLEDs emitting light even when crumpled between two fingers.

Before assembling the pulse oximeter, Yokota and co-workers separately characterized the light emitters and the photodetector. The PLEDs exhibited quantum efficiencies around 13% at a current density of 10 mA cm^{-2}. When illuminated with a solar simulator at 1 sun, the power conversion efficiency of the OPD was found to be 1.46%, and the spectral responsivity indicates that the detector covers wavelengths between 400 nm and 650 nm.

The flexible oximeter is laminated onto the skin with adhesive tape. When it is wrapped around a finger, the assembled device operates in reflection mode: the two PLEDs emit red and green light into the skin and the OPD collects the light that is reflected back. As with conventional oximeters, the peripheral capillary oxygen saturation can be determined from the ratio of the amplitudes of the reflected green and red optical signals, as the absorption of light by haemoglobin at these wavelengths is sensitive to the level of oxygen in the blood. The organic oximeter shows good stability in air over a few days of operation, and the measurements are in agreement with the read-out from a commercially available system.

Given these encouraging results, the authors anticipate that further optimization of the fabrication of the passivation layer may lead to flexible optical sensors that can be laminated directly onto organs after surgery, or for everyday monitoring purposes of biological functions.

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