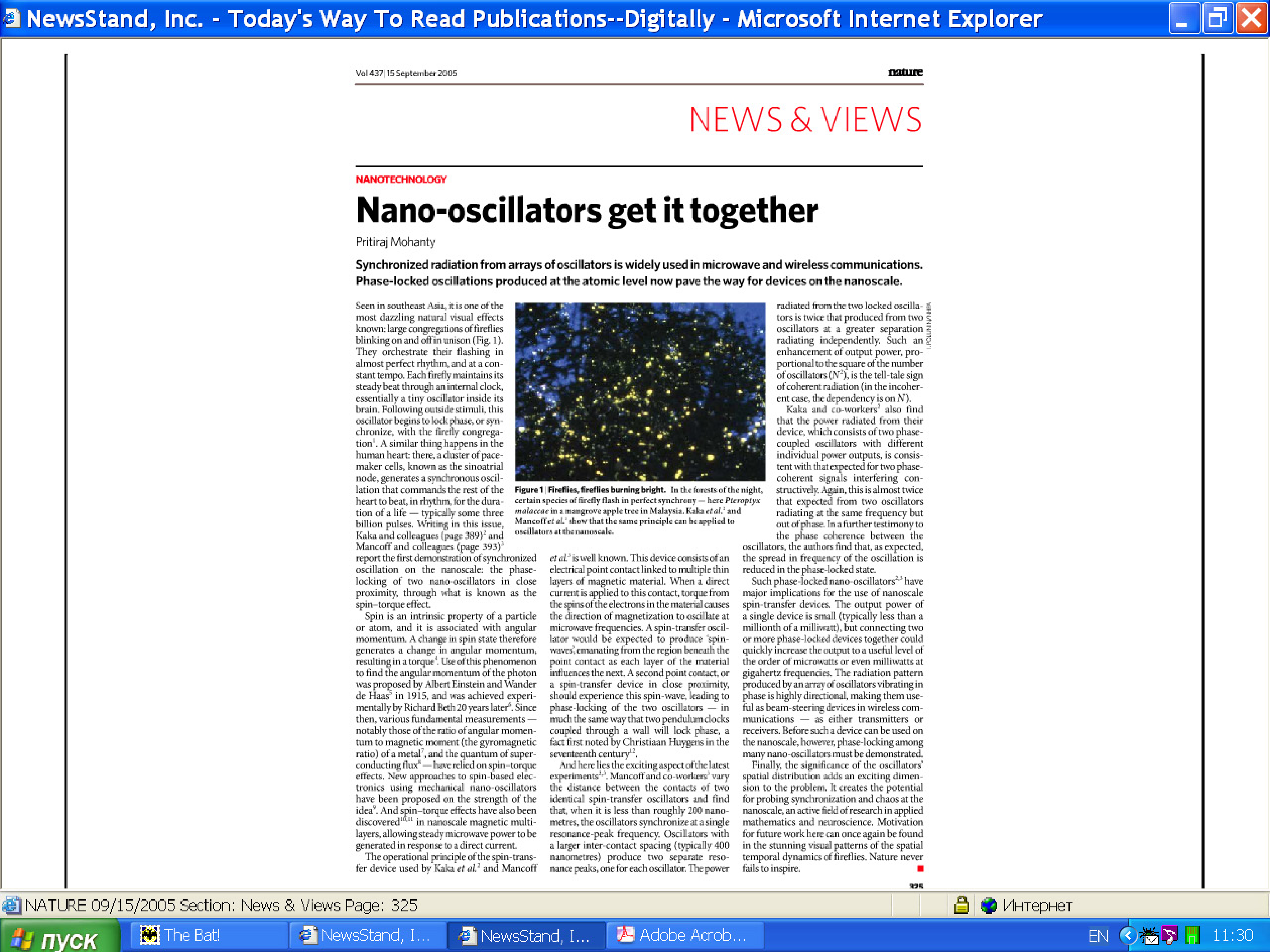

NEWS & VIEWS

NANOTECHNOLOGY

Nano-oscillators get it together

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Synchronized radiation from arrays of oscillators is widely used in microwave and wireless communications. Phase-locked oscillations produced at the atomic level now pave the way for devices on the nanoscale.

Seen in southeast Asia, it is one of the most dazzling natural visual effects known: large congregations of fireflies blinking on and off in unison (Fig. 1). They orchestrate their flashing in almost perfect rhythm, and at a constant tempo. Each firefly maintains its steady beat through an internal clock, essentially a tiny oscillator inside its brain. Following outside stimuli, this oscillator begins to lock phase, or synchronize, with the firefly congregation[1]. A similar thing happens in the human heart: there, a cluster of pacemaker cells, known as the sinoatrial node, generates a synchronous oscillation that commands the rest of the heart to beat, in rhythm, for the duration of a life — typically some three billion pulses. Writing in this issue, Kaka and colleagues (page 389)[2] and Mancoff and colleagues (page 393)[3] report the first demonstration of synchronized oscillation on the nanoscale: the phase-locking of two nano-oscillators in close proximity, through what is known as the spin–torque effect.

Figure 1 | Fireflies, fireflies burning bright. In the forests of the night, certain species of firefly flash in perfect synchrony — here *Pteroptyx malaccae* in a mangrove apple tree in Malaysia. Kaka *et al.*[2] and Mancoff *et al.*[3] show that the same principle can be applied to oscillators at the nanoscale.

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Spin is an intrinsic property of a particle or atom, and it is associated with angular momentum. A change in spin state therefore generates a change in angular momentum, resulting in a torque[4]. Use of this phenomenon to find the angular momentum of the photon was proposed by Albert Einstein and Wander de Haas[5] in 1915, and was achieved experimentally by Richard Beth 20 years later[6]. Since then, various fundamental measurements — notably those of the ratio of angular momentum to magnetic moment (the gyromagnetic ratio) of a metal[7], and the quantum of superconducting flux[8] — have relied on spin–torque effects. New approaches to spin-based electronics using mechanical nano-oscillators have been proposed on the strength of the idea[9]. And spin–torque effects have also been discovered[10,11] in nanoscale magnetic multilayers, allowing steady microwave power to be generated in response to a direct current.

The operational principle of the spin-transfer device used by Kaka *et al.*[2] and Mancoff *et al.*[3] is well known. This device consists of an electrical point contact linked to multiple thin layers of magnetic material. When a direct current is applied to this contact, torque from the spins of the electrons in the material causes the direction of magnetization to oscillate at microwave frequencies. A spin-transfer oscillator would be expected to produce 'spin-waves', emanating from the region beneath the point contact as each layer of the material influences the next. A second point contact, or a spin-transfer device in close proximity, should experience this spin-wave, leading to phase-locking of the two oscillators — in much the same way that two pendulum clocks coupled through a wall will lock phase, a fact first noted by Christiaan Huygens in the seventeenth century[12].

And here lies the exciting aspect of the latest experiments[2,3]. Mancoff and co-workers[3] vary the distance between the contacts of two identical spin-transfer oscillators and find that, when it is less than roughly 200 nanometres, the oscillators synchronize at a single resonance-peak frequency. Oscillators with a larger inter-contact spacing (typically 400 nanometres) produce two separate resonance peaks, one for each oscillator. The power radiated from the two locked oscillators is twice that produced from two oscillators at a greater separation radiating independently. Such an enhancement of output power, proportional to the square of the number of oscillators (N^2), is the tell-tale sign of coherent radiation (in the incoherent case, the dependency is on N).

Kaka and co-workers[2] also find that the power radiated from their device, which consists of two phase-coupled oscillators with different individual power outputs, is consistent with that expected for two phase-coherent signals interfering constructively. Again, this is almost twice that expected from two oscillators radiating at the same frequency but out of phase. In a further testimony to the phase coherence between the oscillators, the authors find that, as expected, the spread in frequency of the oscillation is reduced in the phase-locked state.

Such phase-locked nano-oscillators[2,3] have major implications for the use of nanoscale spin-transfer devices. The output power of a single device is small (typically less than a millionth of a milliwatt), but connecting two or more phase-locked devices together could quickly increase the output to a useful level of the order of microwatts or even milliwatts at gigahertz frequencies. The radiation pattern produced by an array of oscillators vibrating in phase is highly directional, making them useful as beam-steering devices in wireless communications — as either transmitters or receivers. Before such a device can be used on the nanoscale, however, phase-locking among many nano-oscillators must be demonstrated.

Finally, the significance of the oscillators' spatial distribution adds an exciting dimension to the problem. It creates the potential for probing synchronization and chaos at the nanoscale, an active field of research in applied mathematics and neuroscience. Motivation for future work here can once again be found in the stunning visual patterns of the spatial temporal dynamics of fireflies. Nature never fails to inspire. ■