preserves the last few storm deposits before the earthquake? Are there enough analyses to rule out coincidence; that is, do all areas undergo both transient uplift and subsidence on this scale, during the interseismic period, and some are just caught at the time when a significant marker (a large earthquake) occurs?

But if pre-seismic subsidence does occur, what might be the mechanisms? A hypothesis suggested by both groups[1,2] is the occurrence of 'slow earthquakes' along a deeper part of the subduction zone than the part that ruptures during great earthquakes. Such slip[7] recurs about every 14 months at Cascadia[8]. But theory has not predicted and observation has not documented subsidence at coastal locations from these slow earthquakes. Moreover, in Cascadia these 'earthquakes' have occurred since the Global Positioning System (GPS) network was installed in 1992, and they appear to happen regularly[8]. Indeed, if the authors' hypothesis is correct, it would predict an imminent great earthquake in Cascadia.

A good test of the idea might have been possible if the Sumatra region had been intensively monitored in the decade before the massive earthquake that occurred on 26 December 2004 — but hindsight is a wonderful commodity. Some parts of coastal areas along subduction zones have been instrumented with networks of continuous GPS sites in the past 10–15 years. But few areas in the world yet have precise and dense enough coverage with geodetic arrays to detect slow earthquakes; measuring vertical motions is even more of a challenge. Nonetheless, those systems that are in place are helping us to understand the fundamental mechanics of subduction zones. Whether this behaviour predictably includes precursor coastal subsidence remains an open question. ■

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SOLID-STATE PHYSICS

Light at the end of the channel

Francisco J. Garcia-Vidal

If photonic circuits are ever to compete with their electronic counterparts, strong confinement of light waves coupled with low propagation losses is needed. A new class of waveguides offers both.

Miniaturized circuits that use light to carry digital information would be inherently faster than conventional electronic circuits, and have a capacity thousands of times greater. But there's a snag: the development of practical, small photonic components is impeded by the diffraction limit — the fact that light will spread out on passing through any region narrower than its wavelength. On page 508 of this issue[1], Bozhevolnyi *et al.* flag a new route around this obstacle. They present the first components that guide and manipulate light in the form of so-called channel plasmon–polaritons. These guide the light along the bottom of sub-wavelength V-shaped grooves, milled in a metal film, without high propagation losses.

Channel plasmon–polaritons are young members of an extended family known as the surface plasmons. These are electromagnetic waves that originate in the collective excitation of free electrons at the interface of a metal and an insulating dielectric, such as air. Surface plasmons remain tightly bound to the interface: a plasmon of an optical wavelength — between about 400 and 750 nanometres — penetrates around 10 nm into the metal and decays over a few hundred nanometres in the dielectric.

Surface plasmons thus concentrate light in a volume less than its wavelength across. They can also be used to transmit electromagnetic signals: for the near-infrared wavelengths around 1.5 micrometres, typically used in telecommunications, the propagation length of a plasmon at a planar gold–air interface is about a millimetre, and therefore long enough to connect two devices on a chip optically. The use of surface plasmons is also compatible with available planar electronics technology, also offering the possibility of transporting optical signals and electrical current on the same substrate.

But to create miniature photonic circuits, surface plasmons have to be confined not just in the direction perpendicular to the interface, but also in the plane of the interface, so that they can propagate efficiently through narrow metal strips. This has proved problematic: when a propagating plasmon is squeezed from the sides, its propagation length is severely reduced[2]. The several strategies deployed to circumvent this problem all represented an imperfect trade-off between sub-wavelength lateral confinement and propagation length.

In short, a new actor was needed: enter the channel plasmon–polariton (CPP). The fundamental idea of guiding light along the bottom of milled V-grooves in a planar metal surface was proposed[3] 15 years ago and subsequently refined[4]. Compared with other plasmons, these channel modes are laterally strongly confined and suffer only low propagation loss. Extensive numerical simulations[5] have confirmed this, and also showed that so-called single-mode operation — meaning that, at a given wavelength, energy (information) is transmitted at one speed — can be attained in such waveguides simply by adjusting the depth of the grooves. (Single-mode operation is advantageous where optical interconnectors are used, because in multi-mode operation, light can jump between modes at a junction, provoking a distortion in the shape of the light pulse.) That finding was followed by the prediction last year[6] that transmission of light through a sharp 90° bend in a CPP waveguide was possible almost without loss. Waveguides created in dielectric materials with a 'photonic band-gap' (that is, in which light in a certain wavelength range cannot propagate through the bulk structure) could do the same job, but only at the price of a much larger device.

So much for the theory. On the experimental side, too, things have begun to evolve rapidly. Just eight months ago, Bozhevolnyi and colleagues reported[7] the experimental achievement of CPP propagation along a straight, V-groove waveguide drilled in a gold film using focused ion-beam milling. Working at telecommunication wavelengths between 1.4 and 1.6 μm, they used a near-field optical microscope to build up a picture of the propagation all along the waveguide. They thus showed that the light was confined to a width of around 1 μm that was less than its wavelength, and had a propagation length of 90–250 μm, depending on the exact wavelength.

In their latest contribution[1], Bozhevolnyi *et al.* fabricate the first CPP-based optical components. The first of these is a 'Y-splitter', a junction in which two straight waveguides are connected to a third over a distance of only 5 μm, just over three times the light's wavelength. This feature is of paramount importance for the implementation of miniature optical circuits on a chip.

As a proof of principle, the authors also demonstrate very high performance for a Mach–Zehnder interferometer (in effect, two Y-splitters fork-on-fork that can split and then reunify a light beam) and a functional ring resonator. This latter component (see Fig. 3 on page 510) can — according to the phase

difference of the light waves entering and leaving the ring, and therefore the degree of constructive or destructive interference between the two — act as a wavelength filter for the transmitted light.

The fabrication process exploits current planar technology: milling grooves onto a metal film with a focused ion beam is similar to drawing lines on a paper with a pencil. The possibilities for such techniques are huge, but there are still some problems. One is how to get external light into a CPP waveguide and extract it at the other end. Coupling to a standard single-mode optical fibre, as practised by Bozhevolnyi and colleagues[1,7], might produce large losses, and other alternatives should be tested. Nevertheless, the successes already achieved in a very short period of experimental research using channel plasmons to mould the flow of light hint at bright prospects ahead. ■

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MATHEMATICAL PHYSICS

Going to ground

Christos N. Likos

How can one find the minimum total energy of an infinite number of particles? A proof showing that, for certain interactions, periodic 'ground states' exist provides a new perspective on this, one of the oldest questions in physics.

When deciding how particles move and interact, nature has an affinity for minimum values. In newtonian mechanics, particles choose trajectories that minimize action, a quantity with the dimensions energy × time. In thermodynamics, a collection of particles at a fixed volume and temperature will settle into a state that minimizes the so-called free energy of the system, a quantity that, at absolute zero, reduces to the total energy — that is, the sum of all the interactions between pairs of the particles.

Simple as such statements may seem, the task of finding 'ground-state' configurations, and proving that they do indeed minimize the energy of a system, is notoriously difficult. The standard approach is more or less trial and error: one chooses a number of configurations, calculates their energies, and picks the structure with the smallest energy as the ground state.

Writing in *Physical Review Letters*[1], András Sütő short-circuits this process. He demonstrates with a strikingly powerful mathematical argument that, in certain cases, the ground-state configuration sought when a material freezes into a regular crystal structure is a periodic one. Certain formal criteria must be met: first, the pair-interaction potential $\varphi(r)$, which describes the potential energy of a two-particle system in terms of their separation, r, must possess a mathematical analogue known as a Fourier transform. (This transform expresses the potential as a series of oscillating sine and cosine terms that depend on a parameter k, the wavenumber, which represents an inverse wavelength.) Additionally, the Fourier-transformed potential, which is written $\hat{\varphi}(k)$, must be positive for all values of k below some threshold value, K_0, and zero for all values above it.

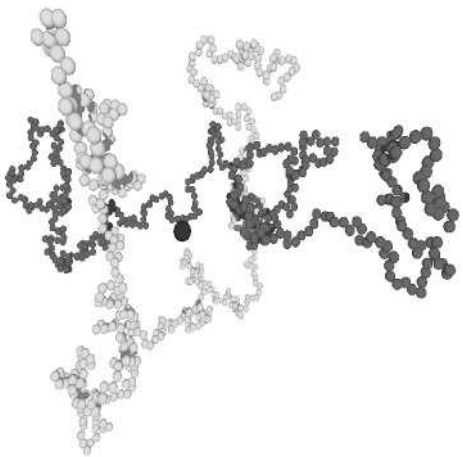

Figure 1 | Chain overlap. A snapshot from a simulation involving two self-avoiding polymers. In this configuration, the centres of mass of the two chains (denoted by the big sphere) can fully overlap. Sütő's results[1], showing that for certain interactions periodic ground states exist, deal with a similar type of interaction that was long considered 'unphysical'. (Courtesy of Arben Jusufi.)

The Fourier description of the potential is convenient for potentials such as those considered by Sütő, because it allows the total lattice energy — the energy required to bring all particles infinitely far apart from each other — to be expressed as a simple mathematical formula. The advantage of the Fourier representation is clearly seen when the potential not of particle pairs, but of a periodic lattice of particles, is considered. Such a spatial lattice — a direct, or Bravais, lattice — also has a Fourier representation, known as the reciprocal lattice.

In the reciprocal lattice, the total energy of the system (the quantity we wish to minimize) is simply the sum, up to K_0, of the lattice potentials $\hat{\varphi}(\mathbf{K})$ for all reciprocal-lattice vectors $\mathbf{K}$ that build up the lattice. (For a three-dimensional reciprocal lattice, each $\mathbf{K}$ will have three wavenumber components, and so uniquely define a point in the lattice.) Whereas the term at $\mathbf{K} = (0, 0, 0)$ represents the origin of the coordinate system and is therefore the same for all types of lattices, all other allowed energy contributions, and thus the total energy of the system, depend on the exact spatial configuration of the particles in the direct lattice.

Imagine now a direct lattice (call it X) for whose reciprocal lattice all non-zero reciprocal-lattice vectors define points outside a sphere of radius K_0. In this case, the total energy of the system will include only the term at $\mathbf{K} = (0,0,0)$. But for all other lattices with at least one value of $\mathbf{K}$ smaller than K_0, the total energy can only be larger, because the additionally contributing potentials $\hat{\varphi}(\mathbf{K})$ are, by our definition, positive. So X must have the minimum possible energy.

Sütő[1] proved his point by showing that, for a three-dimensional lattice and at the minimum particle density for which his results apply, given by $\rho^* = K_0^3/(8\sqrt{2}\pi^3)$, the body-centred cubic (bcc) lattice that many metals assume indeed fulfils the above requirements. With increasing density, other lattice types join the group, producing an infinite number of ground-state configurations. Moreover, Sütő demonstrated that periodic ground-state configurations are stable against arbitrary deviations from periodicity, and that aperiodic unions of periodic configurations minimize energy.

These are remarkable achievements. But why did such a clear and powerful proof take so long? The answer probably lies in the peculiar form of $\varphi(r)$, which implicitly demands a finite potential at zero separation — the equivalent of permitting two particles to overlap each other fully. In the case of interacting atoms, however, a strong repulsive force is created between bound electron shells and their quantum-mechanical wavefunctions because of the Pauli exclusion principle (which holds that no two particles such as electrons may occupy