suggests that the density of Cooper pairs remains unchanged in the CuO_2 layers, which may allow the realization of almost decoupled 2D stacks with a Kosterlitz–Thouless superconducting transition. Interlayer coupling would simply allow 3D superconductivity to develop, yielding a larger value of the 3D ordering temperature. An alternative scenario suggests that the condensed state does not survive in the absence of the Josephson coupling[7]. This work could have potential applications in signal transmission and light switching, once the gating field can be controlled to allow the phase differences to reach multiples of π and π/2. ❒

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FUNDAMENTAL OPTICAL PHYSICS

The quest for zero refractive index

A superlattice comprising alternating layers of negative-refractive-index photonic crystals and positive-refractive-index dielectric media has been shown to exhibit an effective refractive index of zero. Experiments show that light passing through such a material experiences no phase shift.

Jörg Schilling

During the early years of research into metamaterials, many scientists strived to fabricate structures with negative refractive index (n). Recently, some interest has shifted towards the realization of materials that exhibit zero or near-zero refractive index. A refractive index of zero implies that light enters a state of quasi-infinite phase velocity and infinite wavelength. It also means that every point within the metamaterial experiences a quasi-uniform phase of the light wave present, as though all the dipoles inside the metamaterial are oscillating in unison. Thus, the shape of the wavefronts leaving the metamaterial depends solely on the shape of the exit surfaces of the metamaterial, which provides high flexibility in the design of phase patterns[1]. A simple planar slab of a zero-n material could, in principle, function as a highly selective angular filter that allows the transmission of plane waves only at normal incidence. By applying convex or concave surfaces, the outgoing wavefronts could be either divergent or focusing.

The uniform phase distribution of light within such a material may also have far-reaching consequences for light emission. Placing an emitter inside a zero-n material creates a radiation field with spatially uniform phase inside the material, which produces a highly directional and collimated outgoing beam at an extended planar surface[2]. Because the phase is spatially independent, the exact position of the radiation source inside the zero-n material seems to be irrelevant and the formation of a single collimated beam from many spatially distributed point sources should be possible.

Researchers have attempted to realize a material with zero refractive index (or zero permittivity, ε) through several different strategies. One suggestion was to use metallic metamaterial structures such as stacked frequency-selective surfaces. Alternative approaches include the use of microwave waveguides close to the mode cut-off[3] and the combination of negative- and positive-index materials[4,5].

Serdar Kocaman and colleagues, reporting in this issue of *Nature Photonics*[6], have now constructed a one-dimensional (1D) periodic superlattice from alternating strips of unpatterned regions of positive-refractive-index dielectric media and 2D negative-refractive-index photonic crystals. Using phase-sensitive interferometric measurements, they have demonstrated that light of a specific frequency propagating through such a superlattice experiences no change of phase. Thus, from a macroscopic view point, the superlattice exhibits an effective refractive index ($\bar{n}$) of zero.

The layered structure is formed in slab waveguides that have been fabricated on silicon-on-insulator substrates by structuring the thin top silicon layer. Each superlattice period, Λ, consists of two sections with widths of d_1 and d_2 (Fig. 1). The first section (width d_1) contains a 2D photonic crystal with a hexagonal pore array fabricated by electron beam or deep-ultraviolet lithography. The second section (width d_2) is an unpatterned section of the waveguide slab. The period and pore radius of the photonic crystal section were chosen in such a way that light with a wavelength of λ_0 = 1,552 nm couples to a mode of the second photonic band of transverse-magnetic-like polarization. Because the second photonic band has a negative slope within the first Brillouin zone, the group velocity appears negative, meaning that the directions of phase propagation and energy propagation are counter-parallel. Kocaman *et al.* describe this propagation by a negative refractive index n_1 whose absolute value is derived from the band structure within the first Brillouin zone.

The phase of a wave travelling through the photonic crystal section changes by $\Delta\varphi_1 = n_1 d_1 k_0$, where k_0 is the free-space wavenumber. Because the refractive index n_1 is negative, the phase of the wave actually evolves backwards and accumulates a negative relative phase in the photonic crystal layer. However, when the wave propagates through the subsequent unpatterned section with positive refractive index n_2, its phase changes by $\Delta\varphi_2 = n_2 d_2 k_0$. Because the refractive index of this layer is positive, the phase evolves forwards and the negative phase accumulated in the photonic crystal layer 'unwinds'. If the ratio between the two superlattice layer thicknesses, d_1/d_2, is adjusted to give $\Delta\varphi_1 = -\Delta\varphi_2$, the net phase change of the wave ($\Delta\varphi_1 + \Delta\varphi_2$) after traversing the whole superlattice

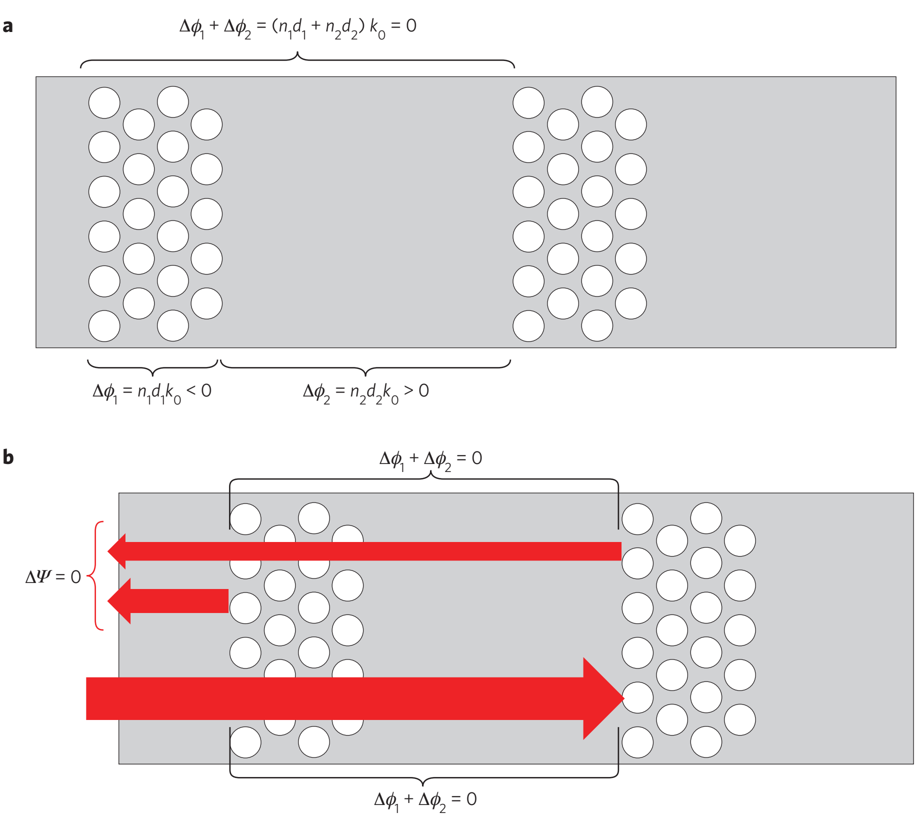

Figure 1 | Phase delays in a zero-$\bar{n}$ superlattice. **a**, A superlattice with an effective refractive index of zero can be realized by combining negative-refractive-index photonic crystal sections (width d_1) and positive-refractive-index unpatterned waveguide sections (width d_2). Negative and positive phase changes ($\Delta\varphi_1$ and $\Delta\varphi_2$) cancel out at the design wavelength, leading to an overall phase change of zero ($\Delta\varphi_1 + \Delta\varphi_2 = 0$) over the whole superlattice period. **b**, Development of the zero-*n* bandgap. Because the average refractive index over each superlattice period is zero, the optical path length and the accumulated phase $\Delta\Psi$ for all the Bragg-reflected waves is also zero. The interference of all the Bragg-reflected waves is therefore always constructive and independent of the length of the superlattice period, which results in a zero-*n* bandgap.

period Λ is zero; that is, the effective index of the superlattice is $\bar{n} = 0$. However, this condition can only be fulfilled for a single wavelength because n_1 is highly dispersive and a near-zero $\bar{n}$ can only be obtained in a narrow spectral range. To experimentally demonstrate a zero-*n* material, Kocaman *et al.* employed two strategies.

First, the researchers observed the formation of the zero-*n* bandgap in transmission measurements. Bragg reflection generally leads to the formation of bandgaps in photonic crystals. For the case of a zero effective index in the superlattice, the phase difference between the wavelets of light reflected at the first superlattice period and those reflected at subsequent periods is zero. This corresponds to the zeroth order of the Bragg condition. This zero-*n* bandgap was observed in the transmission spectra as a dip between wavelengths of 1,550 nm and 1,565 nm. To demonstrate that the observed dips are indeed due to the expected zero-*n* bandgaps, Kocaman *et al.* prepared several superlattices with different periods Λ, but kept the ratio d_1/d_2 constant. The observed spectral independence of the bandgap position from the period of the superlattice gives a clear indication that the observed bandgap is indeed the expected zero-*n* bandgap.

Second, Kocaman *et al.* used an interferometric technique to monitor the relative phase change of the wave travelling through the superlattice. The superlattice structure was included in one arm of a Mach–Zehnder interferometer, whose second arm represented a reference, unstructured waveguide. Interference fringes appeared in the transmission spectra after the light from both arms was rejoined, owing to the inherent difference in optical path length. The researchers observed that adding further superlattice periods (and thus extending the geometric path for light travelling through the superlattice arm) does not change the position or spectral period of the interference fringes within the spectral range of the zero-*n* bandgap. They also changed the length of the superlattice period but again did not observe an impact on the position or period of the interference fringes within the zero-*n* bandgap. Changing the number or length of the superlattice periods therefore did not influence the accumulated phase of the light propagating through the superlattice, even though the geometric path length in the superlattice was being varied. This is only possible if the superlattice periods do not contribute to the phase accumulation because the optical path length within the superlattice is zero, which corresponds to $\bar{n} = 0$.

Through these phase-sensitive measurements, Kocaman *et al.* demonstrated that a superlattice consisting of alternating 2D photonic crystal and unpatterned waveguide sections can exhibit an effective refractive index of zero while also providing zero relative phase delay. Furthermore, they showed that the average refractive index $\bar{n}$ can be controlled by adjusting the relative thicknesses of the superlattice period (d_1 and d_2). Tuning the ratio d_1/d_2 shifts the spectral position of the zero-*n* bandgap and thus achieves complete phase compensation for another wavelength. It is therefore possible to fulfil the zero-*n* condition at nearly any desired wavelength, which provides enhanced flexibility in system design.

Using dielectric photonic crystals to provide the negative refractive index avoids Ohmic losses, which are intrinsic to metallic metamaterials. This is particularly important for structures operating at visible and near-infrared frequencies because their comparatively deeper penetration into metals causes significant losses. Ohmic dissipation, which is related to the conversion of electromagnetic energy to phonons (heat) through the damping of free electrons in the metal, is not present in a dielectric material. However, even photonic crystal superlattices made from nearly lossless dielectric materials suffer from systematic transmission losses due to scattering and out-of-plane diffraction. The period of the superlattice is several micrometres in length, which allows it to function as a grating coupler that can diffract light out of the thin silicon slab, thereby lowering transmission levels in the waveguide. This fact has already been used to observe light propagation through a similar superlattice structure[5]. Furthermore, the zero-*n* bandgap exists at the design wavelength, where the zero-*n* condition is exactly fulfilled. This causes considerable back-reflection, which reduces transmission levels, especially when the number of superlattice periods is increased. These effects therefore limit the size of structure that can practically be employed before the intensity of the transmitted light becomes too low.

It is useful to compare the negative refractive indices found in metal metamaterials and dielectric photonic crystals, given the key role played by the negative refractive index section of the superlattice in the work of Kocaman *et al.* In metamaterials, a negative refractive index is usually achieved by combining two different kinds of resonators (wires and split rings) driven at a frequency slightly above their resonance. Each resonator therefore radiates more than 90° out of phase with their individual excitation, leading to both negative permeability and negative permittivity — 'backwards' waves. Although such individual resonators do not exist in photonic crystals, the generation of backwards-evolving waves is achieved by Bragg reflection due to the periodic variation of the refractive index. Whereas metamaterials avoid diffraction by using subwavelength-sized structures, photonic crystals use diffraction as the source for negative-refractive-index behaviour.

It should be noted that the description of wave propagation through a periodic structure with a single negative refractive index could be misinterpreted if care is not taken. A wave in a periodic structure travels as a Bloch mode, which is represented by a sum of many plane waves with different directions of propagation and spatial periods (both defined by their wave vector). For example, the wave vector of the jth plane wave is defined by the condition $\mathbf{K} + \mathbf{G}_j$, where $\mathbf{K}$ is the wave vector in the first Brillouin zone and $\mathbf{G}_j$ is any reciprocal lattice vector (j being an integer). This multitude of wave vectors makes it non-trivial to define a single refractive index. The absolute phase change of each plane wave component is different along the considered propagation direction. Over an integer of N periods of propagation in the photonic crystal, the phase change is $\Delta\varphi_{1,j} = n_1 d_1 k_0 + Nj2\pi$. However, the additional term — an integer multiple of 2π — is irrelevant when evaluating interferometric results; only the negative relative phase change $n_1 d_1 k_0$ has an impact. This relative phase change matches the negative absolute phase change of the plane wave component of the first Brillouin zone considered by Kocaman *et al.*, and therefore justifies the description of wave propagation through the photonic crystal slabs by a negative refractive index for the described situation.

The superlattice approach is currently restricted to 1D propagation. However, 2D wave propagation is desirable to realize sophisticated phase-shaping schemes. In addition, a zero-n material with curved entrance and exit surfaces might be of interest for new optical elements that take advantage of the zero accumulated phase or uniform phase within the structures. Whether or not this can be achieved using photonic crystal superlattices remains to be seen. ❐

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ATOM OPTICS

Marriage of atoms and plasmons

The interaction between atoms in a Bose–Einstein condensate and plasmon-enhanced fields is a step towards the goal of realizing hybrid atom–polariton systems for tasks in quantum information processing.

James P. Shaffer

Surface polaritons and atoms can both be quantum objects, yet their unique characteristics make them suitable for different tasks. Atoms can be isolated from their environment and manipulated precisely with lasers, which makes them good candidates for storing information and building single-photon sources, traceable sensors and quantum gates. Surface polaritons, in contrast, are capable of interfacing with solid-state devices and being moved around on a surface using micro- and nanostructures. They are therefore an attractive means of transporting quantum information from one point to another on a microscopic chip, perhaps between different clouds of trapped atoms. The individual advantages of atoms and polaritons can be combined to allow the realization of sophisticated circuits.

One important future goal is to develop efficient hybrid quantum devices in which individual excitations can be transferred between atoms and polaritons on demand, thus allowing both systems to be used to their maximum advantage. Information-processing circuits that exploit both atoms and surface polaritons and operate using the principles of quantum entanglement are an important example of what might be achievable in the future.

Although such hybrid atom–polariton systems are still a long way from fruition, the work of Stehle *et al.*[1] demonstrates an important preliminary step towards their realization. Writing in this issue of *Nature Photonics*, Stehle *et al.* report the interaction of a Bose–Einstein condensate (an ultracold collection of atoms that share the same quantum state and thus behave as a single entity) with small customized surface potentials. The potentials were created from the plasmonic electromagnetic fields formed by tailored metallic microstructures on the surface of a prism. It is hoped that such potentials could eventually be used to guide atoms around circuits.

Surface plasmons are a type of surface polariton that result from the coupling between an electromagnetic field and collective oscillations of the conduction electrons in a metal. They can be created using light and propagate along the