part-way through its transit from one end to the other.

A recent *Nature Photonics* Commentary[6] sets out some of the key reasons why photonics researchers have become interested in slow light. Perhaps the strongest argument for a PC-based approach is the capability of producing compact devices that have small operating power requirements, such as switches and modulators[7,8]. Using slow light also enhances various nonlinear effects, such as all-optical switching and the Raman effect, which can provide amplification.

We have now arrived at the start of the era of silicon photonics. This technology borrows heavily from silicon electronics, for example silicon-on-insulator (SOI) wafers are now used in photonic integrated circuits. Slow light propagation in silicon waveguide structures offers compactness, together with acceptably small device insertion loss. There also exists the possibility of compact gain structures integrated on-chip with the slow-light devices. But there are continuing challenges for silicon. The delay-line storage capacity achieved so far is modest when compared with the capabilities of optical fibre. For instance, Baba and co-workers[9,10] have achieved values approaching 60 for the delay–bandwidth product using a particular (chirped) form of PC channel waveguide. Another issue is propagation loss. It is probable that propagation losses as low as $0.1\ \mathrm{dB\ cm^{-1}}$ in strongly confined silicon photonic nanowire waveguides will be achievable — a value that is ‘only’ five orders of magnitude larger than the loss value for silica fibres. Photonic-crystal channel waveguides typically have larger propagation losses, with around $1\ \mathrm{dB\ cm^{-1}}$ being a practical lower limit. Also, the rule is that slower light is subject to a greater propagation loss, scaling inversely with the group velocity.

Notomi and co-workers have gone well below the benchmark group velocity of $0.01c$ (where c is the speed of light in a vacuum) while retaining good device performance. The structures have as many as 150 cavities coupled sequentially, and delays as large as 125 ps could be obtained. This was achieved in devices with a length on the order of 200 μm and a total ‘footprint’ on the order of $1{,}000\ \mu\mathrm{m}^2$, a remarkably low figure compared with other recent work[5]. But with an emerging pulse width as large as 21.5 ps resulting from an input pulse with a spectral width of 1 nm, the ratio of the delay to the pulse width was only 5.8. Also, the transmission spectrum provided clear evidence of the deleterious effects of structural disorder. This is practically unavoidable when producing nominally identical repeating structures, even when the best technology available is used[11]. Another concern is the threat of the Anderson localization, as observed by Mookherjea and co-workers[12] and discussed by Vardeny and Nahata[13]. This will worry device engineers even if it provides intellectual stimulation for physicists. Nonlinearity will probably accentuate the impact of disorder-induced localization.

The accessibility to different points on the device provides switchable and tunable delay[5], and this will probably be a key factor in the successful exploitation of CROW structures. We should now expect the emergence of PC coupled-resonator delay lines with as many as 100 distinct resonators together with individual resonator control. If these structures can hold at least a byte of light pulses, such delay lines might provide an interesting direct manipulation capability for information streams that systems engineers will find useful. The technological challenges remain large, but the potential rewards are commensurate with these challenges.

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GEOMETRICAL OPTICS

The dynamics of spinning light

The effect of spin on the trajectories of polarized light beams has now been experimentally observed, with results that agree with the predictions of Berry phase theory.

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The geometric phase[1,2] is pervasive in quantum and classical physics, including condensed-matter science, optics and chemistry. The best known example of this phase is Berry's phase[1], which is generated by the slow (that is, adiabatic) quantum evolution of a physical system — either in coordinate, momentum, or even an abstract parameter space. Within this regime, the evolution is described by the ‘parallel transport law’, which brings a geometrical beauty to the description of complex physical systems.

The Berry phase[1,2] is widely known as a general geometrical concept underlying the slow evolution of many physical systems. It is less known, however, that the Berry phase is not only a passive geometrical phenomenon, but also an active, dynamic effect. On page 748 of this issue, Konstantin Bliokh *et al.*[3] report an experimental verification of transport effects originating from Berry phase geometrodynamics by observing tiny spin-related trajectory deflections of circularly polarized light beams propagating along helical paths inside a glass cylinder.

The Berry phase arises from the coupling between ‘fast’ and ‘slow’ degrees of freedom. As the slow variables (or adiabatic parameters) evolve, the fast variables acquire a Berry phase. But every action has a reaction, and the fast degrees of freedom produce a back-action on the evolution of the slow variables. An example of this appears in the Born–Oppenheimer

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approximation in atomic and molecular physics. There, the fast and light electrons acquire geometric phases during the evolution of the slow and heavy nuclei, and, at the same time, the nuclei experience a reaction from the electrons[2].

Remarkably, this reaction takes the form of a ‘geometric force’ arising in the equations of motion of the slow variables. This force is a Lorentz-type transverse force produced by an effective geometric magnetic field — the so-called Berry curvature, which was first considered a purely geometrical concept. Indeed, the geometric curvature can seem to be a field producing a real force. Such close geometrodynamical interrelations are typical, for example, in general relativity, where a real physical field appears as a geometrical characteristic of space.

Transverse geometrical forces affect the motion of a variety of physical objects: a magnetic moment in a space-varying magnetic field[4]; a two-dimensional quantum vortex in a superfluid[5] (where the geometric force produces the Magnus effect); and a spinning particle in an external field[6–9]. In the case of a spinning particle in an external field, the Berry-phase geometrodynamics describes the effects of the spin–orbit coupling between the fast internal degrees of freedom (spin) and the slow motion of the particle (its trajectory). The reaction of the spin on the particle trajectory produces a topologically induced transverse deflection of the particle — the spin Hall effect. This effect has recently attracted considerable attention in condensed-matter[6,7], optical[8] and high-energy[9] physics.

In this issue, Bliokh and colleagues[3] report experimental observation of the spin-dependent topological transport of photons. By launching a laser beam at a grazing angle to the internal surface of a glass cylinder, the light propagates along a smooth helical trajectory as a result of total internal reflection. Such a helical path (schematically shown in Fig. 1) induces a spin–orbit coupling between the geometry of the trajectory and the intrinsic spin angular momentum carried by the polarized light. The theory and experiment reported by Bliokh *et al.*[3] in this issue provide a fairly complete picture of the geometrodynamical evolution of polarized light. On the one hand, the trajectory determines the variations of the polarization of light through the Berry phases acquired by the circularly polarized modes. On the other hand, a spin-dependent perturbation of the trajectory occurs, which deflects the right- and left-handed circularly polarized beams in opposite directions tangent to the cylinder surface (see Fig. 1). This is a remarkable ‘spin Hall effect of light’.

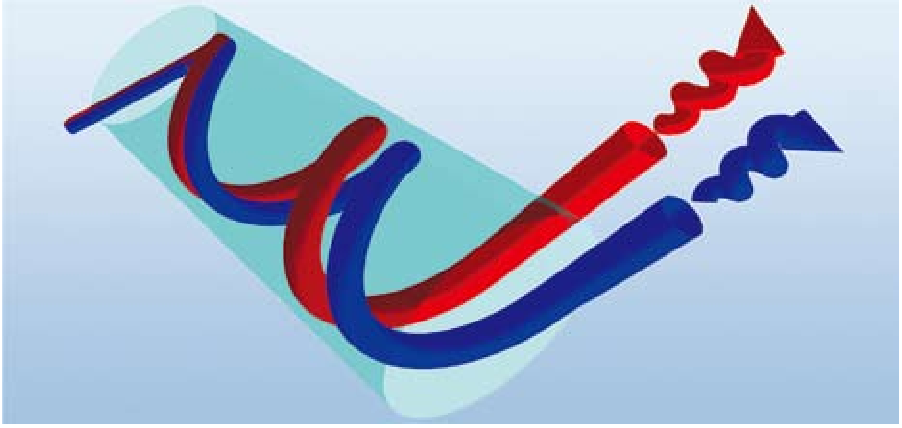

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Figure 1 A schematic diagram showing the trajectories of left- (in blue) and right-handed (in red) circularly polarized light beams along the reflecting surface of a glass cylinder (turquoise). The spin–orbit coupling between the intrinsic angular momentum (spin) of light and the curved-propagation trajectory produces opposite deflections for the two beams. This is the spin Hall effect of light described by a Lorentz-type transverse velocity term originating from a topological monopole in momentum space.

Although the typical magnitude of this effect is a fraction of a wavelength, its non-local character allows its accumulation along the helical trajectory[8], yielding an output displacement of up to several wavelengths.

Interestingly, the Berry-phase geometrodynamics of polarized light propagating along a smooth curved trajectory is described by the fundamental model of a relativistic spinning particle in an external field. In this manner, the Berry curvature has the form of a topological monopole in momentum space — a concept used in modern theoretical physics and closely related to the so-called space non-commutativity[9]. In the context of the spin Hall effect, the topological monopole produces a real dynamical action on the particle evolution: a Lorentz-type transverse velocity term in the equations of motion. The same formalism underlies the evolution of spinning particles in a curved space–time[9], as well as the motion of electrons in semiconductor systems[6].

The results reported by Bliokh *et al.*[3] seem to be the first direct observation of the trajectory deflection caused by the topological Berry-phase monopole in momentum space. The results may have an impact not only in optics, but also in high-energy and condensed-matter physics. For relativistic particles, measuring the spin Hall effect is far beyond current experimental capabilities, whereas in condensed-matter systems its observation is complicated owing to competing extrinsic effects from impurity scattering[10] and the impossibility of tracing the trajectory of electrons. Thus, the optical field offers a unique and convenient opportunity to measure this weak topological phenomenon.

Here it is worth mentioning another recent paper by Hosten and Kwiat, reporting measurements of the spin Hall effect of light[11]. There, the splitting of right- and left-handed polarizations was observed by the refraction of light at a dielectric interface, using an elegant technique of quantum weak measurements. A transverse spin-dependent shift of an optical beam scattered from an interface, which is also known as the Imbert–Fedorov effect, represents the strong-scattering limit of the spin Hall effect of light. However, as opposed to the adiabatic weak-scattering regime studied by Bliokh *et al.* in this issue[3], the Berry-phase geometrodynamical formalism is inapplicable in that case.

In summary, the effect of spin on the trajectories of polarized light beams has now been experimentally observed, and the results agree with the predictions of Berry phase theory[3]. Topological transport phenomena on the wavelength scale offer a new field for future experiments. In this way, modern nano-optics and photonics, operating with light at subwavelength scales, provide a promising new avenue for exploring these fundamental effects.

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