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Global information exchange and telecommunication take place on a network of optical fibers threaded around the world many times over. The successful operation of such an immense network depends on millions of routers, switches, and processors detecting and directing packets of data. Each of these devices play their part by reading from the same script: detect a packet of digital information encoded on an optical carrier; convert the packet from the optical domain to the electronic domain; operate on the packet; and finally, convert the packet back to the optical domain for its next network hop. The rate at which this highly-choreographed sequence takes place, however, is ultimately limited by the bandwidth of the individual electronic devices at each network node [1, 2].

The continued increase in global network bandwidth demand highlights the need for new devices that reduce the effects of this electronic bottleneck by operating entirely in the optical domain. All-optical devices are capable of controlling one optical signal with another, eliminating the need for optical-to-electronic (O/E) and electronic-to-optical (E/O) conversion. In addition to the goal of increased network bandwidth, there are distinct advantages to operating all-optical devices at the few- or single-photon limit. With devices that operate at the quantum level, a new class of quantum information networks can be implemented where single photons control one another. As an example, such interactions are required in long distance quantum communication schemes [3]. The combined goals of high network bandwidth and single-photon sensitivity motivate the development of ultra-low-light all-optical devices.

For the present, consider one particular device, the all-optical switch. We define an all-optical switch as a device that allows one beam of light to change the output power, direction, or state of polarization of another beam of light that is either propagating through a nonlinear medium or generated within the medium. An all-optical switch necessarily requires a nonlinear optical medium. Unfortunately, the nonlinear response of most materials is small so creating an all-optical switch that operates at the few-photon level requires strong nonlinear light–matter interactions.

Several materials and systems have been used to develop and demonstrate low-light all-optical switches including high-finesse cavities [4, 5], plasmonic nanostructures [6], and quantum-interference effects such as electromagnetically-induced transparency [7–10]. These systems tend to be experimentally complex and most do not lend themselves to miniaturization. To this end, there has also been a notable effort to create all-optical devices using semiconductors where manufacturing and miniaturization processes are well understood. Such systems include semiconductor optical amplifiers (SOAs) [11, 12], spatial solitons in semiconductor microcavities [13], and waveguide-coupled ring resonators in silicon [14]. The tradeoff for working in semiconductors is that these materials have weak optical nonlinearities, hence, they require light levels that are well above the few-photon regime.

In order to implement low-light-level all-optical switching using semiconductors, a new approach must be used. One possible approach is based on controlling transverse optical patterns and was recently demonstrated in an atomic system [15, 16]. In this system, a two-spot pattern is formed when resonant laser beams counterpropagate through a warm rubidium vapor. The orientation of this two-spot pattern was made to change by injecting a perturbation in the form of a weak beam propagating at a slight angle to the pump beam axis. This perturbation beam had several orders of magnitude less power than the generated pattern. A weak control beam, containing as few as 600 photons, is thus able to control the direction of a significantly stronger output beam. A weak input beam controlling a strong output beam means that the device is cascadable, i.e., one device output is sufficient to drive a subsequent device input [2]. The primary drawback of the vapor-based switch is that the response time, ≈3 μs, significantly limits the operational bandwidth.

In this issue, Stefan Schumacher and collaborators [17] propose a semiconductor microcavity system that can be used as an all-optical switch along the lines of Ref. [15].[1] Schumacher et al. develop a theoretical treatment of the coupling between the cavity electric field and the exciton polarization within a typical GaAs microcavity. Based on this treatment, they evaluate a numerical model for the spatio-temporal dynamics of four-wave mixing processes. It is important to note that the physical mechanism that gives rise to four-wave mixing in a semiconductor is very different from that in an atomic vapor. Despite these differences, the relevant processes in the microcavity give rise to gain in off-pump-axis directions, hence, they are responsible for the spontaneous generation of off-pump-axis beams.

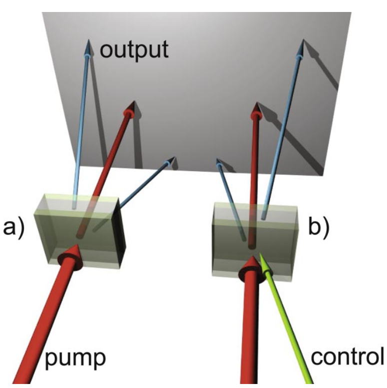

Figure 1 (online colour at: www.pss-rapid.com) A conceptual illustration showing the directional switching of light in a semiconductor microcavity. a) A pump beam (red) induces the emission of off-axis beams (blue) from a semiconductor microcavity. b) A weak off-axis control beam (green) changes the direction of the generated beams.

[1] For a more detailed review of pattern-based all-optical switching in atomic and semiconductor systems, see Ref. [18].

The physical situation corresponding to the numerical model in [17] is illustrated in Fig. 1. An incident pump beam, above a certain pump beam threshold, induces off-axis beams. The generated beams, see Fig. 1(a), propagate with an azimuthal orientation that is determined by slight symmetry-breaking in the cavity. A weak off-axis control beam causes the generated beams to change orientation, thus redirecting the generated beams, see Fig. 1(b). The simulations indicate that a control beam with as few as 13 photons could redirect output beams that are 15 times more powerful.

With several similar features, the proposed semiconductor device maintains key strengths of the original atomic-vapor device with the additional advantage of a nanosecond response time [17]. In addition to being cascadable, the switch exhibits logic level restoration, meaning the output level is consistent regardless of fluctuations on the control input [2]. Logic level restoration is an inherent feature of the device design because the state of the switch corresponds to the output beam direction rather than the output beam power.

Attention should also be paid to a related analysis, by Kheradmand et al. [19], of optical pattern formation in semiconductor cavities. This work investigates the role of external perturbations in selecting the pattern generated in a semiconductor microresonator. Although the model used in [19] assumes a perfect rotational symmetry, an instability seeded by fluctuations in the field and carrier densities results in spontaneous pattern formation. Patterns exhibited by this system include rolls, squares, honeycomb or hexagons; the specific pattern can be selected by the strength of the injected field. An appropriate perturbation, with Fourier components matched to those of the generated pattern, can then be injected to cause the pattern to change orientation. For the case of rolls in the near-field, the far-field pattern is a pair of spots, similar to the case studied by Schumacher et al. [17]. The orientation of these spots can thus be controlled and the device used as an all-optical switch.

Earlier work on pattern-based all-optical switches demonstrated high sensitivity, but the original atomic vapor system suffered from slow microsecond response times. The recent research into the nonlinear optical properties of semiconductor microcavities introduces a promising new route toward few-photon all-optical switching in semiconductor materials. If one considers the early vapor-based all-optical switch to be analogous to the electronic vacuum tube, then perhaps the proposed semiconductor system is the first step toward a solid-state all-optical transistor.

To extend these promising results, with the ultimate goal of an optimized switching device, additional modeling of semiconductor microcavity systems will be necessary. In particular, a full two-dimensional simulation will be able to confirm that the hexagonal pattern assumed by Schumacher et al. is indeed the preferred symmetry of the microcavity system. Although the physical model used in [19] differs from that used by Schumacher et al. [17], the general agreement of these two approaches suggests that there may be a parameter regime that naturally exhibits hexagonal patterns. Finally, experimental observation of pattern formation and directional switching behavior will verify the theoretical foundation of the numerical model and identify potential routes for the optimization of a microcavity-based all-optical switch.

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