All-Optical Switch Controls Strong Beams with Weak Ones

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Switches that are capable of redirecting pulses of light are important components of high-speed optical communication networks. With such devices, an incoming "switching" beam redirects other beams via light-by-light scattering in nonlinear optical material. For quantum information networks, it is important to develop optical switches that are actuated by a single photon.

Unfortunately, the nonlinear optical interaction strength of most materials is so small that achieving single-photon switching is exceedingly difficult. This problem appears to be solved through modern quantum-interference methods, where the nonlinear interaction strength can be increased by many orders of magnitude.[1-4] Another desirable property of all-optical switches is that the output beams are controlled by a weaker switch beam, so they can be used as cascaded classical or quantum computational elements. Current switches, however, tend to control a weak beam with a strong one.

In a recent experimental study, we demonstrated an all-optical switch that operates at low light levels and controls strong beams with weak ones.[5] In our setup, two counter-propagating pump laser beams pass through warm rubidium vapor. When the power of the pump beams is above a critical level, strong nonlinear coupling between the beams and the atoms results in an instability that gives rise to new beams of light emitted along a cone around the pump beams[6] [see figure, part (a)].

Two distinct beams are generated at pump beam powers just above the instability threshold and form a two-spot pattern when observed on a plane perpendicular to the propagation direction (a, b). This two-spot pattern can be rotated by applying a properly aligned switch beam, as shown in (c). Typically, the orientation of the output beams rotates to the direction of the switch beam, and we find that the pattern is most easily perturbed when the switch beam is injected at azimuthal angles of ±60°.

In the absence of a switch beam, we observed the two-spot pattern shown in (b), where the output power is 1.5 μW. The injection of a 2.5 nW switch beam results in a complete rotation of the output beams (d). The switch beam thus controls output beams that are 600 times stronger.

Partial switching can be achieved with a much lower power switch beam. For example, a 230-pW beam switches half of the power from the two original beams into the two rotated beams. Thus, in this case, the switch beam controls output beams that are approximately 6,500 times stronger. Furthermore, an observed 3 μs rise-time implies that the switching is achieved with only about 2,700 photons.

The energy density E, in units of photons per $(\lambda^2/2\pi)$, where $\lambda = 780$ nm is the wavelength of the switch beam, indicates the number of photons needed to actuate a switch whose transverse dimension has been reduced as much as possible.[7] A measured energy density E of fewer than 10^{-2} photons/$(\lambda^2/2\pi)$ suggests that the switch might operate at the single-photon level with system optimization.

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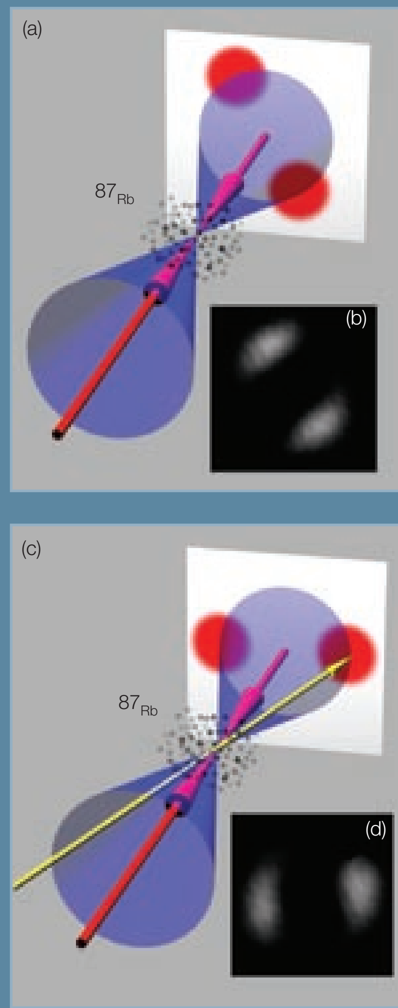

A weak switch beam rotates the two-spot pattern. (a) Two pump laser beams (red) counterpropagate in rubidium vapor, inducing an instability that generates two new beams of light emitted along a cone (blue). The two beams form a two-spot pattern (red). (b) Observed two-spot pattern. (c) A weak switch beam (yellow) rotates the pattern. The pattern is most easily rotated when the switch beam is injected along the cone (blue) and at azimuthal angles of ±60°. (d) Observed rotated pattern.

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