

# Using Transverse Patterns for All-Optical Switching

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**Abstract:** We observe that a transverse optical pattern changes orientation in the presence of an ultra-low-light-level beam. This switch displays transistor-like behavior.

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## 1. Introduction

An important component of high-speed optical communication networks is a switch capable of redirecting pulses of light, where an input “switching” beam redirects other beams via light-by-light scattering in a 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 cascability: that the output beams are controlled by a weaker input beam. In a recent experimental study [5], we demonstrated a cascable all-optical switch that operates at low light levels. Here we present results demonstrating the transistor-like response of our switch.

In our setup, two counterpropagating 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 [6]. The instability gives rise to new beams of light that are emitted along a cone around the pump beams and form patterns in the transverse plane. Well above threshold, the pattern is composed of six spots, but it can contain many spots in a flower pattern for very high powers. For pump beam powers just above threshold, where the switching behavior is optimal, the pattern consists of a pair of spots in both the forward and backward directions; the pattern emitted in one direction is shown in Fig. 1a.

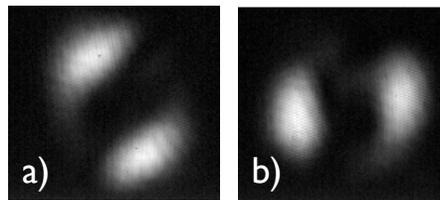


Fig. 1. Generated pattern observed for a pump power just above threshold (630  $\mu$ W in the forward beam and 230  $\mu$ W in the backward beam). a) Initial orientation of the pattern. b) Pattern orientation in the presence of the switching beam.

By injecting a weak switch beam into the vapor at a small angle to the pump beams (along the cone of the generated light), we can change the orientation of the two spot pattern as shown in Fig. 1b. This weak beam acts as the input to the system by controlling the direction of the output beams that form the pattern.

## 2. Switch Response

The orientation of the patterns is extremely sensitive to the presence of the switch beam. The sensitivity is maximized when the switch beam is aligned with the pattern symmetry. Specifically, the switch is most sensitive when the pattern is rotated by  $60^\circ$  relative to the original output pattern. For this optimal alignment, we have observed full and partial switching with input powers of 3 nW and 230 pW respectively [5]. With a typical response time of 3-4  $\mu$ s, the lowest power corresponds to partial actuation of the switch with as few as 2700 photons. The switch sensitivity can be compared to other all-optical devices using the energy density given in units of photons per  $(\lambda^2/2\pi)$ . This metric gives the number of photons needed to actuate a switch with a transverse dimension that has been reduced to the diffraction limit of the interacting beams. Our switch can fully respond to  $\sim 10^{-2}$  photons per  $(\lambda^2/2\pi)$  and partially respond to  $\sim 10^{-3}$  photons per  $(\lambda^2/2\pi)$ . This represents a significant improvement over the best EIT-based switch to date which operates at 1 photon per  $(\lambda^2/2\pi)$  [7].

The full and partial switching responses are analogous to the saturated and active regimes of a transistor, respectively. We have recently measured the response of the switch at various input power levels to characterize this transistor action, as described below.

### 3. Transistor Action

To measure the response of our switch to various input power levels, we inject a sequence of switch-beam pulses with decreasing power. The response is measured by placing a pair of pinholes to spatially select a portion of the pattern. One pinhole selects light from a spot that is present in the pattern during the off state (no switch beam) and the other pinhole selects light from a spot in the on state (switch beam present).

For input powers ranging from 470 pW to ~0 pW the measured response is shown in Fig. 2. The switch fully actuates for the first four input pulses indicating full switching behavior down to 300 pW. Between 245 pW and 115 pW the switch is no longer operating in the saturated regime and responds to the decreasing input power by transferring only some of the output power from the off spots to the on spots. This partial switching is analogous to a transistor's active response regime.

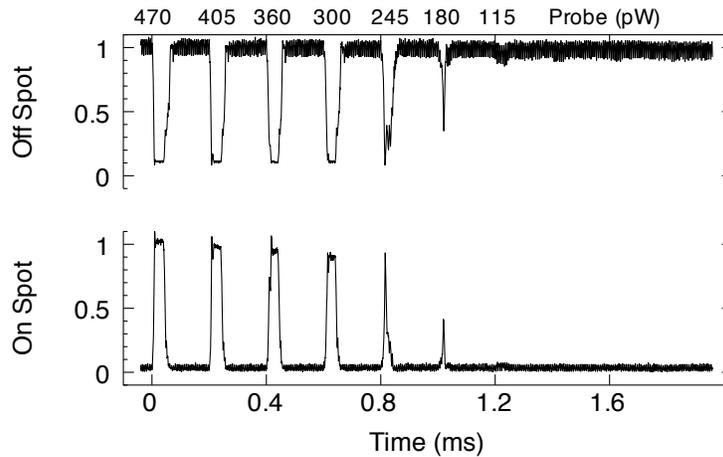


Fig. 2. Response to pulses with decreasing input power. Pulses from 470 pW to 0 pW. The switch fully actuates down to 300 pW, exhibits partial switching to 180 pW and responds only slightly to input powers between 140 pW and 50 pW.

We find that careful alignment of the switch beam to the pattern symmetry, and precise control of the density of the atomic vapor yield a sharp transition from saturated response to null response, and hence a narrow active region. The sharpest transition indicates the highest sensitivity to the switch beam and therefore the lowest number of input photons required to fully actuate the switch. Additionally we find that the switching photon number is roughly constant in the saturated regime because the response time of the switch increases for decreasing switch beam power. The response times of the pulses shown in Fig. 2 range from 4  $\mu$ s to 10  $\mu$ s. For partial switching, the response time is slightly shorter, and the total number of photons needed for partial switching is typically lower than the total number of photons needed to saturate the switch response. Full switching occurs with ~9,000 photons while partial switching occurs with as few as 3,000 photons.

The high sensitivity and transistor-like response of our switch make it a promising system for use as a logical element in ultra-low light level optical networks. We are currently addressing several effects that may increase the number of photons required to actuate the switch such as stray magnetic fields that pin the pattern orientation and the gaussian pump beam profile that contributes to a bifurcation that causes spontaneous pattern rotation.

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