# Observation of ultra-low-light-level all-optical switching

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## ABSTRACT

Photonic circuits require elements that can control optical signals with other optical signals. Ultra-low-light-level operation of all-optical switches opens the possibility of photonic devices that operate in the single-quantum regime, a prerequisite for quantum-photonic devices. We describe a new type of all-optical switch that exploits the extreme sensitivity to small perturbations displayed by instability-generated dissipative optical patterns. Such patterns, when controlled by applied perturbations, enable control of microwatt-power-level output beams by an input beam that is over 600 times weaker. In comparison, essentially all experimental realizations of light-by-light switching have been limited to controlling weak beams with beams of either comparable or higher power, thus limiting their implementation in cascaded switching networks or computation machines. Furthermore, current research suggests that the energy density required to actuate an all-optical switch is of the order of one photon per optical cross section. Our measured switching energy density of ~$4.4 \times 10^{-2}$ photons per cross section suggests that our device can operate at the single-photon level with modest system improvement.

**Keywords:** All-optical switching, ultra-low-light-level, nonlinear optics

## 1. INTRODUCTION

A fundamental building block of optical communication networks is a switch capable of redirecting pulses of light. Of great current interest is the development of all-optical switches that operate at ultra-low energies, where an incoming "switching" beam redirects other beams via light-by-light scattering in a nonlinear optical material. The switch should be able to control a beam of light that is more powerful that the switching beam, making it possible to cascade switching elements for general-purpose computing applications. For quantum information networks, it is important to develop optical switches that are actuated by a single photon. Unfortunately, most existing all-optical switches can only control a weak beam with a much stronger switching beam, and the nonlinear optical interaction strength of most materials is so small that achieving single-photon switching is exceedingly difficult.

The primary purpose of this paper is to describe a new type of all-optical switch that combines recent developments from two different research communities. It is based on instability-generated transverse spatial patterns, where the direction of the beams associated with the patterns is controlled with a weak input switching beam. The patterns arise from an instability that occurs when laser beams counterpropagate through a warm rubidium vapor and is due to mirror-less parametric self-oscillation. The threshold for self-oscillation is lowered by inducing large ground-state coherence in the rubidium atoms, which increases the switch sensitivity. The observed switching energy density is well below that obtainable with other methods that use laser-driven atoms, and it uses an exceedingly simple experimental setup.

### 1.1. Low-light-level all-optical switching

One possible method for enhancing the nonlinear interaction strength for single-photon applications is to use a medium consisting of a gas of atoms possessing narrow resonances and to tune the frequency of the laser beams near these resonances. The downside of this approach is that the light is often heavily absorbed by the atoms. Recently, it has been shown that the effects of absorption can be essentially eliminated while enhancing the strength of the nonlinearity using electromagnetically induced transparency (EIT), where an intense "coupling field" renders the atom

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transparent via a destructive quantum interference effect.[1] Schmidt and Imamoglu[2] showed that the nonlinear refractive index of a gas of atoms can be enhance by over ten orders-of-magnitude in comparison to standard approaches when they considered the use of four-level atoms in an EIT configuration. They proposed that single-photon generation and switching is possible when the atoms are placed in a cavity.[3] Taking a related approach that relies nonlinear absorption, traveling-wave fields, and the slow-light effect that is present in EIT systems, Harris and Yamamoto[4] proposed a switching scheme using four-level atoms where, in the ideal limit, a single photon at one frequency causes the absorption of light at another frequency. In all of these schemes, however, the switching beam has to be much stronger than the beam controlled by the switch.

The experimental implementation of these proposals is somewhat challenging because the narrowest possible atomic resonances are required to achieve the lowest switching energies, which can be obtained, for example, using atom cooling and trapping methods.[5] Following this approach, Yan *et al*.[6] demonstrated absorptive switching of a weak probe beam using a 1-μs-long switching pulse containing ~$3 \times 10^8$ photons at 780 nm, corresponding to an energy of 65 pJ. In a refined setup, Braje *et al.*[7] demonstrated switching of a weak probe beam using a 350-ns-long pulse with ~$10^7$ photons (2.3 pJ).

In principle, the performance of a switch can be optimized by placing it in a waveguide whose cross-sectional area is of-the-order-of a square wavelength $\lambda^2$. As proposed by Keys,[8] one metric that can be used to infer the behavior of a switch under optimum conditions is to determine the switching energy density in units of photons per square wavelength. The greatest switching sensitivity occurs for the case when the resonance of the atoms comprising the switching medium is naturally broadened. In this case, the atomic resonance cross section $\sigma = \lambda^2/2\pi$ is essentially equal to the minimum waveguide cross-sectional area. Based on this line of reasoning, Harris and Yamamoto proposed a new metric in which the energy density is measured in units of photons per $\sigma$. They predict that the energy density of their proposed EIT-based switch[4] is 1 photon/$\sigma$, which is the equal to the energy density assumed by Keys[8] in estimating the minimum power that must be dissipated to undertake a single optical logic processing step. Using the Harris-Yamamoto metric, Yan *et al*. (Braje *et al*.) observed a switching energy density of ~50 photons/$\sigma$ (~23 photons/$\sigma$), which is only an order-of-magnitude larger than the predicted minimum value. This result indicates that it should be possible to reach the minimum switching energy density with modest system optimization (*e.g.*, greater atomic number density, longer ground-state coherence times, etc.).

Other related low-light-level experiments include modifying the correlation between down-converted photons using a single photon,[9] achieving large Kerr nonlinearity with traveling-wave fields[10] and with atoms placed in a cavity,[11] and multi-wave mixing using few-photon pump fields.[12, 13]

### 1.2. Switching using spontaneously-formed transverse optical patterns

For all of the proposals described in the previous section, the path toward single-photon switching is to enhance the atom-field interaction strength using quantum interference effects. A rather different approach is to take advantage of collective instabilities that occur when laser beams interact with a nonlinear medium.[14] As an example of instability, consider the case when laser beams counterpropagate through a nonlinear medium. For sufficiently large nonlinear interaction strength, it is known that mirror-less parametric self-oscillation can cause the intensity[15, 16] and state of polarization[17-19] to display stationary, periodic or chaotic behavior, and can cause the profile of the laser beams in a plane transverse to the propagation direction to undergo a spontaneous change in pattern.[19-21]

The transverse pattern can take the form of rings, stripes, or hexagons in the near field, which correspond to the emission of light along cones centered on the pump beams in the form of a ring, two spots (with mirror symmetry about the cone axis), or six spots (with 6-fold symmetry) in the far field, respectively. The cone polar angle is of the order of several milliradians and is determined by interference between two different nonlinear processes: forward and backward four-wave mixing.[20-24] Under other conditions, the transverse pattern can display optical turbulence.[25] We stress that instabilities arise from the collective atom-field interactions; they cannot be inferred only by considering the single-atom response to applied electromagnetic fields.

With regards to low-level optical switching, it is known that instability-generated transverse patterns are exceedingly sensitive to tiny perturbations such as that arising, for example, from a weak auxiliary laser beam that is injected into the nonlinear medium.[26, 27] The spots that appear in the far field due to the instability can be thought of as the "output beams" emanating from an optical switch, whose direction and intensity is controlled by the weak auxiliary "switching beam."

Much of the previous work on controlling transverse patterns has focused on the case when a passive or active (population inverted) nonlinear material is placed in an optical resonator, which can give rise to optical bistability, cavity solitons, and turbulence in the transverse profile of light passing through the cavity. It has been shown that cavity solitons can be written and erased throughout the transverse aperture of the device,[27] and spatial-temporal instabilities can be controlled using weak, spatially filtered feedback.[26] In many of the experimental investigations, a semiconductor material[28] (liquid crystal device[29]) is used as the nonlinear material for which the nonlinear coupling coefficient (response time) was low (slow), thus requiring a large switching energy density in comparison to the atomic experiments described in Sec. 1.1. For comparison, one of the lowest reported energy densities needed to write a cavity soliton in a semiconductor microcavity is ~900 photons/σ.[30]

### 1.3. Ultra-low-light-level optical switching: Combining the best of both worlds

From the previous discussion, it is apparent that transverse optical patterns arising from collective instabilities has the possibility of realizing a switch for which the output beam is much stronger than the switching beam (allowing it to be cascaded in an optical switching network), but there is no clear path toward single-photon operation. We find that it is possible to realize an ultra-low-light-level all-optical switch by combining the enhanced nonlinear interaction strength achievable with narrow atomic resonances and quantum interference effects (Sec. 1.1) with instability-generated transverse optical patterns (Sec. 1.2) arising when laser beam counterpropagate through a warm rubidium vapor. In the sections below, we describe our preliminary experimental results on this new class of all-optical switch.

## 2. OBSERVATION OF TRANSVERSE OPTICAL PATTERNS

In our experiments, we investigate the stability of transverse optical patterns of laser beams counterpropagating through a $^{87}$Rb vapor when the frequency ν of the beams is tuned near the $5S_{1/2} \leftrightarrow 5P_{3/2}$ transition (780 nm transition wavelength). The beams are derived from the output of a frequency-stabilized continuous-wave Ti:Sapphire laser, which are spatially filtered using a single-mode optical fiber with angled ends, and collimated to a spot size (1/e field radius) of 470 μm. The input power of one of the beams (denoted as the forward beam) is held fixed at a value of 630 μW and measurements are made for various input powers of the other beam (denoted as the backward beam). Polarizing beam splitters are placed in each beam so that the input beams are linearly polarized with parallel polarizations. Our experiment to characterize the instability involves measuring the power and spatial pattern of the light emitted from the vapor in the forward direction in the state of polarization orthogonal to that of the input beams, as shown schematically in Fig. 1. We find that the threshold for instability-generated patterns depends sensitively on the detuning of the laser from the atomic resonance, the atomic number density, stray magnetic fields, and the precision to which the two beams are counterpropagating. We note that similar instabilities have been observed previously when laser beams counterpropagate through a sodium vapor.[18, 19]

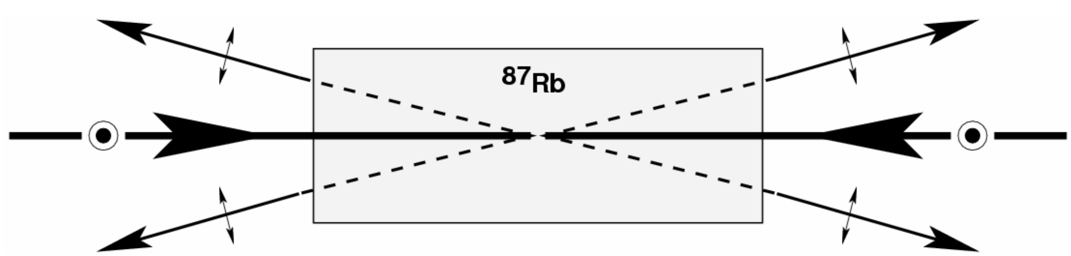


**Figure 1** Schematic of the experimental setup. Linear and copolarized counterpropagating laser beams give rise to orthogonally polarized spatial patterns that are emitted from the vapor along conical surfaces.

The isotopically-enriched rubidium vapor (>90% $^{87}$Rb) is contained in a 5-cm-long glass cell heated to 70 °C, corresponding to an atomic number density of ~7 × $10^{11}$ atoms/cm$^3$, which is tilted with respect to the incident laser beams to prevent possible oscillation between the uncoated windows. The cell has no paraffin coating on the interior walls to prevent depolarization of the ground-state coherence, nor does it contain a buffer gas that would slow diffusion of atoms out of the pump laser beams. The Doppler-broadened linewidth of the transition at this temperature is ~550 MHz. To prevent the occurrence of magnetically-induced instabilities, we us a Helmholtz coil to cancel the ambient magnetic field component along the direction of the counterpropagating laser beams. We believe it is not necessary to use an isotopically-enriched rubidium vapor; it is used a matter of convenience.

Figure 2 shows the laser-frequency dependence of the power emitted in the orthogonal-polarization component and in the forward direction as the laser frequency is scanned through the $^{87}$Rb $5S_{1/2} \leftrightarrow 5P_{3/2}$ transition for the case when the power in the backward beam is equal to 245 μW. The tick marks indicate the positions of two of the hyperfine components of the transition using the notation FF', where F (F') denotes the total angular momentum of hyperfine state of the $5S_{1/2}$ ($5P_{3/2}$) level. It is seen that there exists several sub-Doppler features. The frequency of the generated light for all features is nearly degenerate with the input laser beams, and the large central feature occurring to the high frequency side of the $5S_{1/2}$ (F=1) $\leftrightarrow$ $5P_{3/2}$ (F'=1) transition displays a weak periodic modulation that has a characteristic frequency of ~300 kHz.

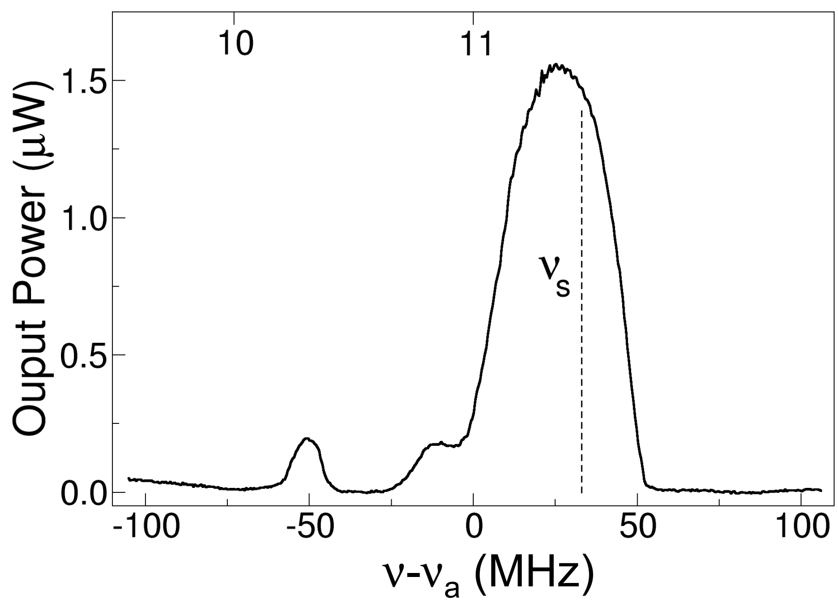


**Figure 2** Spectrum of the instability. Total power emitted in the orthogonal polarization in the forward direction as a function of the laser frequency. The $^{87}$Rb $5S_{1/2}$ (F=1) $\leftrightarrow$ $5P_{3/2}$ (F'=1) transition is denoted by $\nu_a$. The vertical dashed line indicates the laser frequency $\nu_s$ that we use in the switching experiments described in Sec. 3.

We next describe our observation of the instability threshold when the laser frequency is set to the value, denoted by $\nu_s$, used in the switching experiments described in the next section. Figure 3 shows the total power emitted in the orthogonal polarization in the forward direction as a function of the power of the backward beam. The data indicates the existence of a second-order phase transition and it is seen that the output power grows linearly with the power of the backward beam beyond the instability threshold. The threshold occurs at a power of ~125 μW, for a total input power (foward + backward) of 755 μW. The observed instability threshold (total power and atomic number density) for mirror-less parametric self-oscillation is very low and is comparable to or below that obtained by Zibrov *et al*.[31] who used a more complicated experimental setup ("double-Λ" configuration) designed especially to lower the instability threshold.

The far-field transverse spatial pattern of the light emitted from the vapor cell in the orthogonal polarization is in the form of a ring when the laser beam frequency is set $\nu_s$ and the power of the forward and backward beams is set to a very high value (several mW). The light is emitted along cones centered on the pump beams (Fig. 1) with a polar angle of ~10 mrad. As the input power is decreased, the ring breaks up into 6 spots with 6-fold symmetry.[19, 20, 21] For an even lower power (630 μW forward-beam power, 245 μW backward-beam power), two spots appear in the far field as shown in Fig. 4a, which is recorded using a standard video surveillance camera and frame grabber. The two-spot far-field pattern corresponds to a striped near-field pattern. The spots contain a total power of 1.5 μW and their orientation (azimuthal angle) in the transverse plane is stationary. The azimuthal angle of the spots (and the corresponding beams) is dictated by small asymmetries in our experimental setup (*e.g.*, slight distortion of the pump laser beams as they pass through the cell window, etc.) and can be adjusted by slight misalignment of the pump beams or application of a weak magnetic field.

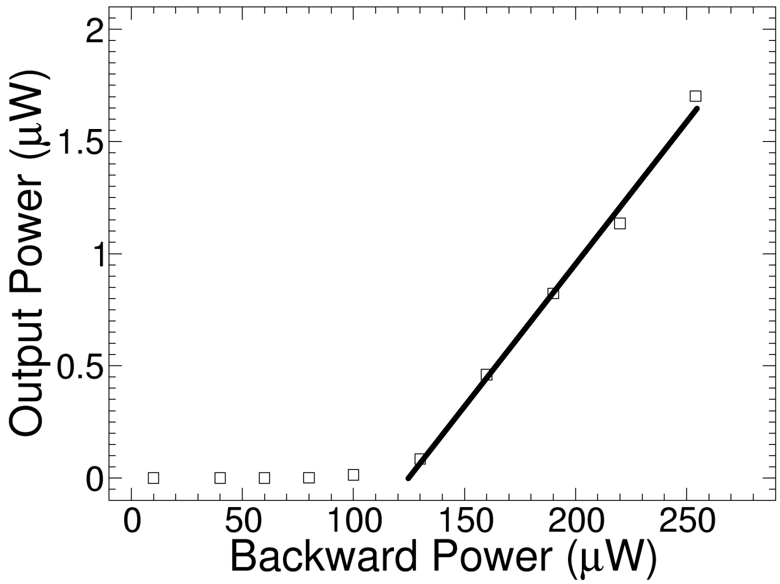


**Figure 3** Instability threshold. The power of the forward beam is 630 μW and the atomic number density is ~$7 \times 10^{11}$ atoms/cm$^3$.

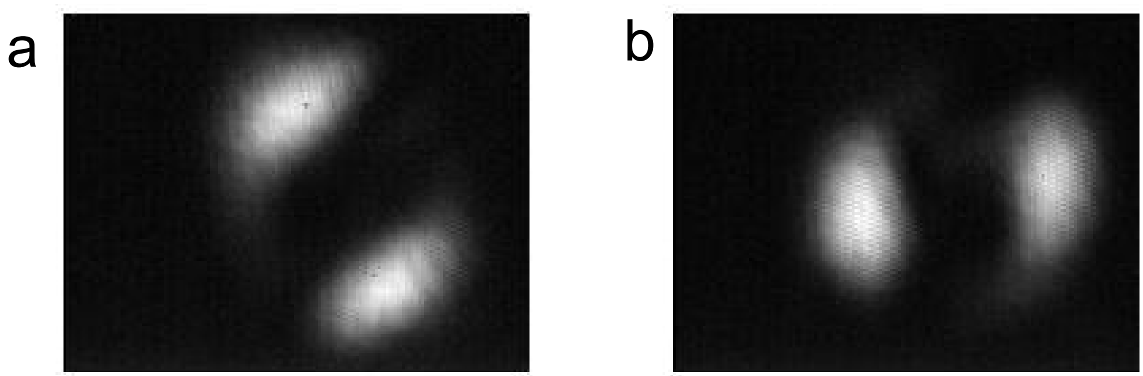


**Figure 4** Ultra-low-light-level all-optical switching. a) Instability-generated transverse spatial pattern emitted in the forward direction, which contains a total power of 1.5 μW. The switch is in the "off" state. b) Transverse pattern in the presence of a 2.5 nW switching beam. The switch is in the "on" state.

## 3. OBSERVATION OF ULTRA-LOW-LIGHT LEVEL SWITCHING

We find that the azimuthal angle of the beams generated by the instability is extremely sensitive to tiny perturbations because the symmetry breaking of our setup is so small. Specifically, directing a weak switching laser beam along the conical surface at a different azimuthal angle causes the beams to rotate to a new angle, with essentially no change in the total power of the pattern.

Figure 1b shows the case when a continuous-wave switching beam is injected into the vapor at an azimuthal angle of -60° with respect to the orientation of the pattern in the absence of the switching beam. The power of the switching beam is $P_s$ = 2.5 nW, which is 600 times smaller than the power contained in the pattern. Typically, the orientation of the output beams aligns with the direction of the switching beam, which is the situation shown in the figure. We find that the pattern is most easily perturbed when the switching beam is injected at aziumthal angles of ±60°, thereby preserving the 6-fold symmetry of the pattern observed for higher powers of the forward and backward beams (see Sec. 2). The results shown in Fig. 4 demonstrate that we can affect the flow of optical power along two different directions with high contrast. Hence, the device could be used as a binary logic element in a computation or communication system, or could be used as a router if information is impressed on the output light (*e.g.*, by modulating the pump beams).

To quantify the dynamic behavior of the device, we turn on-and-off the switching beam with a fiber-based Mach-Zhender amplitude modulator. In the plane of the measurement screen, we place an aperture at the center of one of the spots shown in Fig. 4b (the "on" state of the switch) and measure the power passing through the aperture using an avalanche photodiode. The rise time of the modulation/detection system is ~35 ns, and the spot size (1/e field radius) of the switching beam is equal to 235 μm. Figure 5 shows the temporal evolution of the power passing through the aperture. Weak periodic modulation of the emitted light due to a dynamic instability (see Sec. 2) is apparent when the switch is in the "off" state. Even in the presence of this modulation, the contrast ratio of the switch is at least 4:1. (change in power between the on and off states : sum of the peak-to-peak amplitude fluctuations of both states). We fit a sigmoidal function to the data and find that the rise-time (10% - 90% turn-on time) of the switch is $\tau$=4.1 μs, which we believe is largely governed by the rubidium ground-state optical pumping time.

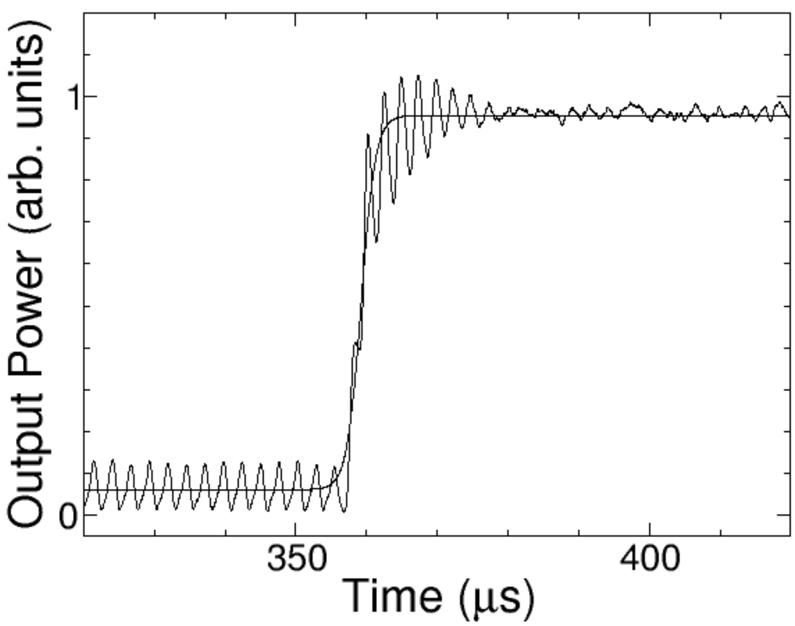


**Figure 5** Response time of the ultra-low-light-level all optical switch. Power passing through an aperture placed in the center of the spot shown in Fig. 4b.

Knowing the switch response time, it is possible to determine its sensitive using various metrics. We find that the number of photons needed to change its state is given by $N_p = \tau P_s/E_p$= 40,000, where $E_p$= 2.54 × $10^{-19}$ J is the photon energy, and the switching energy is equal to $N_p E_p$ = 10 femtoJ. For the spot size of the switching beam used in our experiment, we find that the switching energy density is 4.4 × $10^{-2}$ photons/σ, which corresponds to 11 zeptoJ/σ. The observed switching energy density is at least 500 times smaller that that observed in previous EIT-based all-optical switches[6, 7] and is well below the predicted minimum value (1 photon/σ) that can be obtained with such switches.[4] Furthermore, we use a warm Doppler-broadened vapor whose resonance cross-section is substantially less than the cross-section of a naturally-broadened atomic transition assumed in the analysis of Harris and Yamamoto.[4]

## 4. DISCUSSION

In this section, we discuss some of the implications of our work and suggest possible future research directions. Our switch might be useful in quantum information networks because its spectral and temporal characteristics are well matched to recently demonstrated single-photon sources[32, 33] and storage media.[34] Also, there is a possibility that the spots shown in Fig. 4 are an entangled state of the radiation field[35] and hence the device might be useful for quantum computations.

While speculative, our technique might be useful at telecommunication wavelengths where high-quantum efficiency low-noise single-photon detectors are difficult to realize.[36, 37] For such an application, the rubidium vapor could be replaced with a molecular gas that has resonances throughout the 1.55-μm telecommunication band, such as acetylene or hydrogen cyanide. A single photon can be sensed by directing it toward the laser-pumped gas and detecting its effect on the transverse spatial pattern with a standard photodetector.

In addition, our general method may find application in other scientific disciplines because the spatial patterns used in our switch are a member of a class of patterns displayed by a wide range of nonlinear systems.[38] They are often called dissipative structures and can arise from a Turning or modulational instability. Because modulational instabilities have been observed in matter waves characterizing an ultra-cold quantum gas,[39] one might imagine that atom switching can be possible by perturbing the matter-wave pattern with a few injected atoms.

Our results may also have implications concerning the fundamental limits of general-purpose computation devices. Many years ago, Keys realized that computing power is limited by the energy dissipated by a nonlinear switching element during a logic operation.[8] He considered the behavior of an all-optical switching element consisting of a collection of two-level atoms, where the atoms are made transparent by a switching laser beam whose intensity is high enough to saturate the atomic transition. For a naturally broadened transition, the minimum switching energy density is equal to 1 photon/$\sigma$. Based on this observation, Keys concluded that optical elements can only outperform their electrical counterparts at very high switching speeds. Our observed switching energy density is over a factor of 20 below that assumed by Keys, suggesting that optical devices might be able to outperform electrical ones over a larger range of parameters that his analysis suggests.

## 5. CONCLUSION

In conclusion, we describe our preliminary observation of ultra-low-light-level all-optical switching that can be used as a cascadeable computational element. The switch takes advantage of the extreme sensitivity of spatial optical patterns to tiny perturbations. The observed switching energy density is substantially lower than that achievable with other schemes, putting us on a path toward the realization of a single-photon switch.

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