Switching of light with light using cold atoms inside a hollow optical fiber

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We demonstrate a fiber-optical switch that operates with a few hundred photons per switching pulse. The light-light interaction is mediated by laser-cooled atoms. The required strong interaction between atoms and light is achieved by simultaneously confining photons and atoms inside the microscopic hollow core of a single-mode photonic-crystal fiber.

Keywords: quantum optics, nonlinear optics, atom-light interaction, electromagnetically induced transparency

1. Introduction: Strength of atom-light interaction

The implementation of nonlinear optical processes at low light levels is a long-standing goal of quantum optics. Since the direct effect of light on light in vacuum is extremely weak, such light-light interaction must be mediated by a material system. A gas of cold atoms can serve as a medium that is strongly coupled to the light field. In particular, cold atoms offer strong optical transitions that are broadened only by the radiative lifetime of the excited state, with correspondingly large resonant absorption cross sections of order $\sigma \sim \lambda^2$, close to the maximum value $\sigma_0 = 3\lambda^2/(2\pi)$ possible for a transition of wavelength λ.

In general, large optical nonlinearity is difficult to achieve, and requires long atom-photon interaction times in combination with low photon loss, and tight transverse confinement of the light. To realize a system meeting

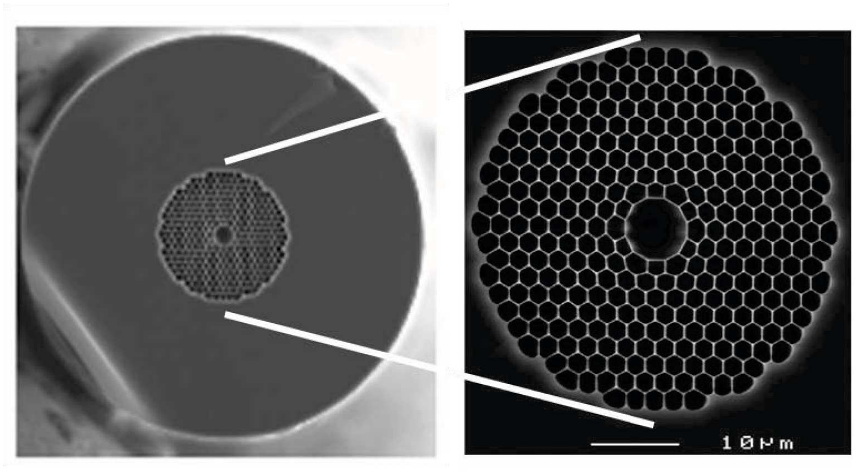

Fig. 1. Hollow-core photonic-bandgap fiber. The diameter of the inner hole, where the atoms are trapped, is 6 μm. The mode waist inside the fiber is 1.9(2)μm. A 3 cm long, vertically mounted piece of fiber is used for the experiments.

these requirements, we trap a mesoscopic ensemble of a few hundred cold rubidium atoms inside a microscopic hollow-core photonic-crystal fiber (PCF, see Fig. 1).[1] The tight transverse confinement of the atoms and of the light within the same one-dimensional waveguide enables strong atom-photon interactions. Using electromagnetically induced transparency[2–6] (EIT) in a mesoscopic regime involving small numbers of atoms and photons, we demonstrate coherent all-optical switching with a few hundred photons per switching pulse, and one to two photons per target pulse.

For simultaneous transverse confinement of light and atoms on a length scale d, the interaction probability between a single atom and a single photon of wavelength λ scales as $p \sim \sigma/d^2 \sim \lambda^2/d^2$, and in our system can approach a few percent. In turn, the atomic medium can be manipulated by pulses containing $p^{-1} \sim 100$ photons. Such a medium enables atom-photon, as well as photon-photon interaction, and exhibits nonlinear optical effects at power levels corresponding to $\sim p^{-1}$ photons per pulse.

Experimental implementation of few-photon nonlinear optics has previously only been accomplished in cavity QED systems, where single atoms are situated in narrow-band, high-finesse cavities,[7] such that a photon interacts multiple times with an atom. Over the last decade, major progress has been made, with several experiments demonstrating nonlinear optical phenomena with single intracavity photons.[8–10] However, these experiments remain technologically challenging and must compromise between cavity bandwidth, mirror transmission, and atom-photon interaction strength. Recently, hollow-core PCFs filled with a molecular gas have been used for significant enhancements of efficiency in processes such as wavelength conversion[11] and four-wave mixing.[12] Several groups have also successfully loaded an atomic vapor into a PCF, for applications such as atomic guiding.[13,14] The recent observations of electromagnetically induced transparency in room-temperature rubidium with nanowatt control fields[15] has demonstrated the promise of these systems for nonlinear optics at very low light levels.

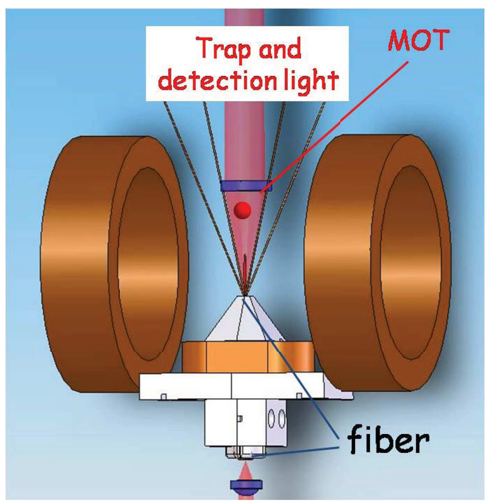

Fig. 2. Setup for loading the hollow-core photonic-crystal fiber with laser-cooled atoms. A magnetic guide consisting of four wires carrying currents assists the loading of atoms from a magneto-optical trap located 6 mm above the end of the fiber. Inside the fiber, the atoms are confined by an off-resonance dipole trap, with the trapping light guided in the fiber. Light is coupled into and out of the fiber using lenses above and below the fiber.

The centerpiece of our experiment is a 3 cm-long piece of hollow-core PCF (Fig. 1), vertically mounted inside an ultra-high vacuum chamber. A laser-cooled cloud of ^{87}Rb atoms is collected into a magneto-optical trap (MOT), focused with a magnetic guide, and loaded into the hollow core of the PCF (see Fig. 2). Inside the fiber, the atoms are radially confined by a far-detuned dipole trap formed by a single beam guided inside the fiber.

The dipole trap is red detuned from the rubidium D_2 line ($\lambda = 780$ nm) by typically a few nanometers, such that the atoms are pulled towards the intensity maximum of the trapping light,[16] i.e. towards the center of the hollow core. Inside the fiber, the small diameter of the guided mode (waist size $w = 1.9(2)\mu$m) results in strong transverse confinement, with radial trapping frequencies on the order of 50 kHz, and a deep trapping potential on the order of 10 mK at guiding-light powers of a few milliwatts.

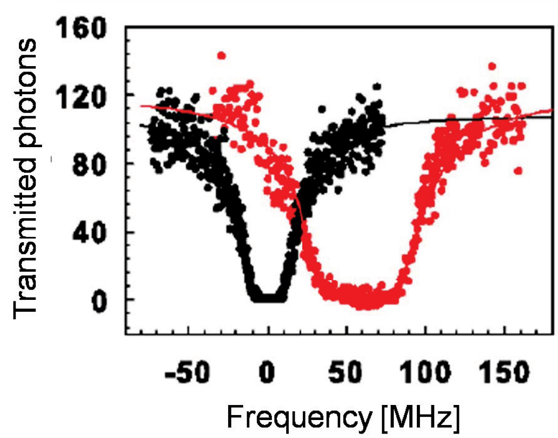

Fig. 3. Absorption of light by atoms inside fiber for continuous trap (red, absorption minimum shifted), and for modulated trap with probing while trap is off (black, unshifted minimum). The frequency shift in the absorption is due to the light shift of the $5S_{1/2} \rightarrow 5P^{3/2}$ transition by the trapping light. The frequency shift that is in agreement with calculations (solid line) provides evidence that the atoms are trapped in the high-intensity region inside the fiber.

To probe the atoms in the fiber, we monitor the transmission of a very-low-power (~ 1 pW) probe beam through the PCF (Fig. 3), detected by a single-photon counter. This probe can be frequency tuned over the D_1 or D_2 resonance absorption lines of rubidium. The dipole trap light introduces a power dependent, radially varying AC-Stark shift, which results in a characteristic inhomogeneous broadening and frequency shift of the absorption profile (red data in Fig. 3). Comparison with the absorption profile calculated from the dipole trap parameters verifies that the atoms are trapped inside the fiber. For the optical experiments described below, we avoid the unwanted perturbation of the absorption profile by synchronously modulating the dipole trap and the probe beam out of phase. The modulation at a rate faster than the trapping frequency allows the atoms to interact with the probe photons only when the dipole trap is off, while the time-averaged optical trap still prevents them from colliding with the fiber wall. We then observe an absorption profile that is completely determined by the natural linewidth of the transition (black data in Fig. 3). From these data we conclude that ~ 100 atoms create an optically dense medium (resonant optical depth $OD = 1$) in the fiber. The absorption profile shown in Fig. 3 corresponds to an optical depth $OD \approx 30$.[17] All optical experiments described below are performed in the modulated dipole trap to avoid inhomogeneous broadening of atomic transitions.

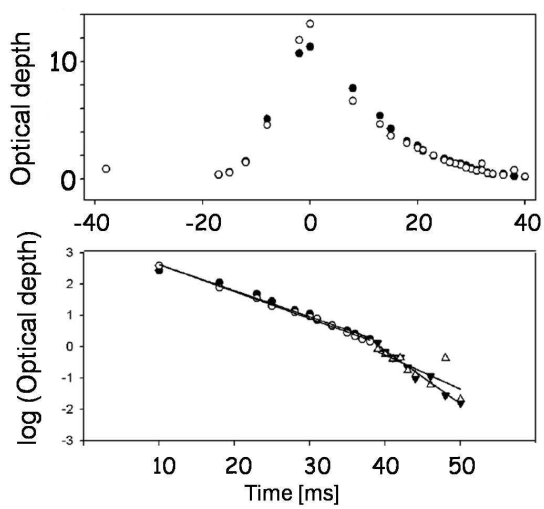

Fig. 4. Lifetime of atoms in hollow-core photonic-bandgap fiber. The figures show the measured optical depth (linear and logarithmic scales) vs. time. The atomic decay for times between 10 ms and 40 ms is exponential with a decay time constant $\tau = 12$ ms. We interpret the kink near 40 ms as being due to atoms leaving the lower end of the fiber. The lifetime increases to 100 ms if the atoms are stopped inside the fiber by one-dimensional Doppler cooling.

The quality of the vacuum inside the fiber is not known, and the gas pressure inside the fiber could substantially exceed that in the main chamber since the extreme aspect ratio of the fiber $L/d \sim 500$ corresponds to very poor conductance. This could result in fast loss of the trapped atoms due to collisions with background gas inside the fiber. We have investigated the trapping by measuring the optical depth vs. time, and the result for the cloud falling through the fiber is shown in Fig. 4. We observe an exponential decay with a time constant of $\tau = 12$ ms for 30 ms, with subsequent faster decay. We interpret the latter, in agreement with simple estimates, as being due to atoms reaching the lower end of the fiber, and having enough energy (supplied by gravity) to leave the fiber in spite of the longitudinal confinement provided by the dipole trap. The data in Fig. 4 may lead one to conclude that the background-gas-limited lifetime of the atoms inside the fiber amounts to 12 ms for our present system.

However, when we stop the falling of the atoms inside the fiber by one-dimensional Doppler cooling along the fiber, we observe much longer trapping times, in some measurements as long as 100 ms. The shorter time constant of 12 ms for the falling cloud may then indicate that the optical trapping potential inside the fiber is not completely smooth, and that it mixes the longitudinal motion (whose kinetic energy is much larger than the radial trap depth) with the transverse motion, resulting in radial loss of the atoms when their radial kinetic energy exceeds the depth of the trapping potential.

2. Incoherent switching of light with light

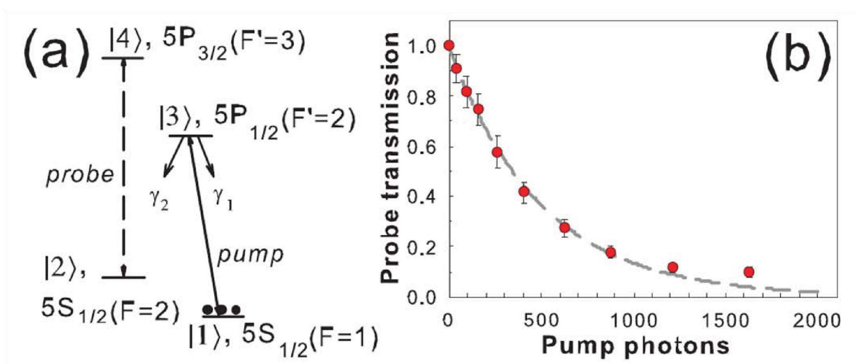

Fig. 5. Incoherent switch using optical pumping. 300 photons coupled into the fiber on the $|1\rangle \rightarrow |3\rangle$ transition are sufficient to cause 50% reduction of the probe on the transition $|2\rangle \rightarrow |4\rangle$.

An incoherent optical switch can be implemented by optical pumping (see Fig. 5). A sample is prepared in the state $|1\rangle$ with an optical depth $OD > 1$ on the $|1\rangle \rightarrow |3\rangle$ transition. Upon excitation on that transition, atoms decay with probability $\gamma_2/(\gamma_1 + \gamma_2)$ from the state $|3\rangle$ into the other hyperfine level $|2\rangle$. When sufficiently many atoms have accumulated in state $|2\rangle$, probe light coupled into the fiber, resonant with the $|2\rangle \rightarrow |4\rangle$ transition, is extinguished.

Fig. 5b shows the extinction of the probe light on the $|2\rangle \rightarrow |4\rangle$ transition as a function of the number of photons incident on the $|1\rangle \rightarrow |3\rangle$ transition. We achieve a 50% reduction of the probe transmission with only 300 pump photons coupled into the fiber. This corresponds to ~ 150 atoms being transferred into the $|2\rangle$ state, which is sufficient to cause the observed absorption of the probe beam.

3. Coherent switching of light with light

The incoherent switch relies on optical pumping by spontaneous emission. It is also possible to implement a coherent method based on EIT (see Fig. 7). Here a control beam is applied on the $|2\rangle \rightarrow |3\rangle$ transition, such that any incident probe photon on the $|1\rangle \rightarrow |3\rangle$ transition is converted into a dark-state polariton,[18] with one polariton component being the atomic-spin-wave excitation to the $|2\rangle$ state. When the control beam is sufficiently weak, corresponding to slow light traveling with velocity $v \ll c$, each incoming photon is converted into an atomic excitation populating the $|2\rangle$ state.

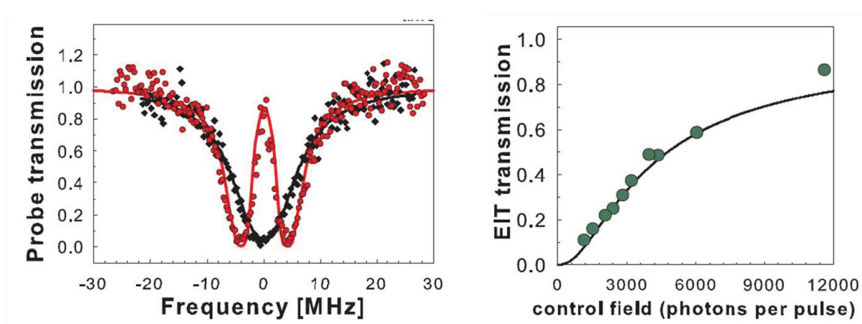

Fig. 6. EIT with weak control field. Left: In the absence of the EIT control beam (black data), the sample is opaque with an optical depth $OD \sim 1$. In the presence of the control beam (red data), a transmission window opens up. Right: Only 10^4 photons per control beam pulse are needed to provide good EIT transmission.

Fig. 6 shows EIT in a sample with optical depth $OD \sim 1$. In the present system the classical control beam itself is quite weak, and as few as 10^4 photons per pulse provide good transparency. For the parameters shown in Figs. 6,7, the pulse is delayed by 30% of its width, or 100 ns. This corresponds to a group velocity of the light on the order of 3 km/s $\ll c$, i.e., to a dark-state polariton that is dominated by the atomic excitation.[18]

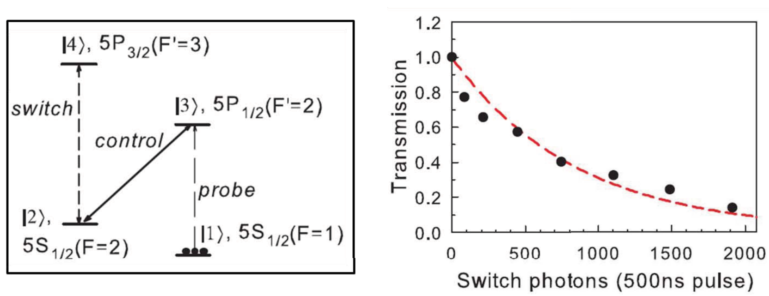

Fig. 7. All-optical switch based on the Yamamoto-Harris four-level scheme. Left: Level diagram with probe, control, and switching field. Right: Transmission of the probe light, normalized to the peak EIT transmission, as a function of the number of photons in the switching pulse.

The coherent switch is based on the four-level scheme proposed by Harris and Yamamoto,[19] as shown in Fig. 7 on the left. The probe light coupling the states $|1\rangle$ and $|3\rangle$ is transmitted on the EIT resonance, unless the switching light is applied on the transition $|2\rangle \rightarrow |4\rangle$. In the latter case, the switching light excites the atomic population in state $|2\rangle$ and destroys the dark-state polariton, thereby reducing the transmission of the probe light.

Fig. 7 (right graph) shows the measured transmission of the probe light as a function of the number of photons per switch pulse. For the oscillator strengths of the transitions used, $\sim$ 700 switch photons result in a 50% reduction of the probe transmission. A contrast of over 90% between the "on" and "off" states of the switch can be achieved with a modest increase in the number of switch photons.[17]

4. Outlook: Towards switching light with a single photon

The number of photons required for the all-optical switch is set by the ratio of mode area to wavelength squared, in combination with the oscillator strengths of the transitions used. To reduce the required switching power further, it should be possible to use a hollow-core PCF with smaller hole diameter. However, the attractive Casimir-Polder force between atoms and fiber walls sets a limit on the hole diameter that lies probably somewhere between 2 and 3 μm.[20] This implies that by reducing the fiber and electromagnetic-mode diameters alone, it will not be possible to reach the limit where a single switch photon can extinguish the probe light.

Further reduction in switch power then requires some form of repeated interaction between the light and the atoms. While in principle external mirrors can be added, such a system will not achieve high finesse due the relatively low efficiency ($\sim 60\%$) of coupling into and out of the fiber. It may be more promising to attempt to integrate some form of Bragg mirrors into the fiber itself.

An alternative is to use quantum optics techniques to realize effective multiple interactions between light and atoms. For instance, it should be possible to build a Bragg grating into the atomic system itself using stationary-light EIT techniques, as demonstrates by Bajcsy *et al.* in free space.[21] Another possibility to enhance the light-light interaction is to set up a double-EIT scheme where both the probe and the switch light are traveling slowly.[22] Both schemes require optical depths $OD \gtrsim 100$,[18,22] which is within reach with modest and incremental improvements of the fiber loading procedure. With such optical depth, it may also be possible to realize a gas of strongly-interacting photons in this one-dimensional system.[23]

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