All-optical modulation of four-wave mixing in an Rb-filled photonic bandgap fiber

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We demonstrate efficient all-optical modulation using Rb vapor confined to a hollow-core photonic bandgap fiber. The intensity of a signal field participating in the four-wave-mixing process is modulated using a weak switching field. We observe 3 dB of attenuation in the signal field with only 3600 photons of switching energy, corresponding to 23 photons per atomic cross section $\lambda^2/(2\pi)$. Modulation bandwidths as high as 300 MHz are observed.

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Nonlinear quantum-optical techniques are being explored to solve problems in optical information processing. A number of schemes for efficient all-optical switches [1–4], all-optical quantum computing gates [5,6], and nondemolition (QND) measurements [7–10] have been either proposed or demonstrated. These approaches require the realization of systems that can achieve measurable nonlinearities at the single-photon level and the development of schemes that can optimally exploit their nonlinear response. Consequently, there is considerable interest in developing media with high optical nonlinearities coupled with tight confinement of the light mode to enhance the intensity. Complementing these efforts are schemes where the frequencies of the interacting light modes and the energy levels of the medium facilitate strong light–matter coupling [2,4,7,10].

Alkali vapors have been used extensively for light–matter interactions due to their large cross section per atom, well-defined energy-level structure, long interaction times, and the large optical depths that can be achieved. Optical waveguides, such as photonic bandgap fibers (PBGFs) with a hollow core, allow an alkali vapor to fill the inside of the guided region and interact with single-mode optical fields. This architecture confines both the atoms and the optical fields transversely to a region that is a few wavelengths in size, which permits weak fields to interact strongly with the atoms over a length that is much larger than the Rayleigh diffraction length. Such systems have been shown to produce strong nonlinearities at ultralow light levels [3,11].

Resonantly enhanced multilevel atomic interactions are attractive for exploiting low-light-level optical phenomena based on quantum interference in alkali atoms. Coherent interactions that exploit narrow resonances have yielded novel nonlinear processes, such as electromagnetically induced transparency [12] and coherent population trapping [13]. For example, in a "lambda" scheme, two optical probe fields couple two ground states of the atom to a single excited state and establish coherence between the two ground states, which results in atom-light states called polaritons. Similar effects can be generated by using a double-lambda scheme, which uses four optical fields to couple the two ground sates to an excited state in a four-wave-mixing (FWM) process [14,15]. These polaritons can interact with other external optical fields and can be used to perturb the atomic ground state coherence resulting in the change in transmission of a probe beam. The external perturbing field, or "switching" field, usually couples one of the ground states to another separate excited state. An on-resonance switching field can be used for low-power all-optical modulation or switching [4], while a slightly off-resonant switching beam can be employed for QND detection schemes [7].

Here we present all-optical intensity modulation of a signal field that is participating in the FWM process with Rb in a hollow-core PBGF. We have previously shown that large optical depths can be generated in a Rb-PBGF system using light-induced atomic desorption [16], which can result in large effective nonlinear susceptibilities and FWM gains greater than 100 with microwatts of pump power [11]. Consequently, introducing a field that can perturb this waveguide-based FWM allows us to study all-optical perturbations of highly nonlinear behavior at extremely low light powers.

The energy-level diagram for our scheme is shown in Fig. 1. We use a double-lambda scheme on the D1 line

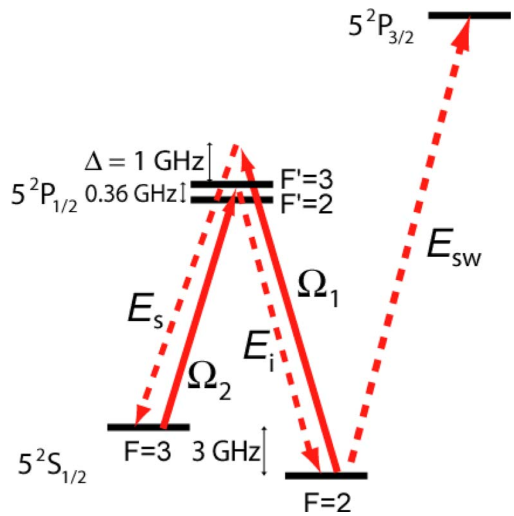

Fig. 1. (Color online) Energy-level diagram of the modulation scheme. FWM is generated in a double-lambda configuration on the D1 ($5^2P_{1/2}$) transition of Rb-85. It is modulated by periodically turning the switching field E_{sw} on to the D2 ($5^2P_{3/2}$) transition.

(795 nm) of Rb-85 to observe FWM with nondegenerate pumps. One pump field Ω_1 is blue detuned by 1 GHz from the $F=2\rightarrow F'=3$ resonance, while the other pump field Ω_2 is tuned between the $F=3\rightarrow F'=2$ and $F=3\rightarrow F'=3$ transitions. A weak signal field E_s blue detuned by 1 GHz from the $F=3\rightarrow F'=3$ transition is also coupled through the PBGF and generates an idler field E_i via the FWM process. The signal is cross polarized with respect to the pump waves, and all three beams are co-propagating in the PBGF. The generated idler is also co-propagating with the same polarization as the signal. The switching field E_{sw}, which is also cross polarized with the pumps, is resonant with the $F=2$ transition of the D2 line (780 nm) of Rb-85.

Figure 2 shows the experimental setup. We use a 3 cm long PBGF (Crystal Fiber AIR-6-800, 6 μm diameter core) that sits inside a vacuum cell with a Rb source attached [16]. The pump beams are combined with the signal and switching beams by using a polarization beam splitter (PBS) cube at the input of the PBGF, which ensures that the polarizations are orthogonal. A small portion of each input field is sent to a reference Rb vapor cell for frequency calibration. A pulsed desorption beam at 808 nm (detuned far from the Rb-85 resonances), which is coupled counterpropagating to the pump and signal waves, is used to generate the desired vapor density and optical depth in the fiber [17]. The vapor density generated in the fiber is such that, in the presence of the pumps (tens of microwatts in power), the signal experiences a gain of 2 at the two-photon resonance (peak of the FWM gain curve). The switching beam is temporally modulated as a triangle wave, at frequencies from 500 Hz – 1 kHz. The modulated signal exits the fiber, is separated from the pumps by a second PBS and from the idler and switching beams by a temperature-controlled etalon (400 MHz linewidth), and is detected by a photomultiplier tube (PMT).

Figure 3(a) shows the modulated signal at 500 Hz with $\sim$1 μW of peak switching power. The input signal power is 5 nW, and its frequency is set exactly at the two-photon resonance so that, at the output of the fiber, the signal power is 10 nW. We see that, in the presence of the switching field, which is modulated at 500 Hz, the signal is attenuated by 50% (3 dB) to 5 nW. The switching field spoils the gain, and the signal passes through the fiber as

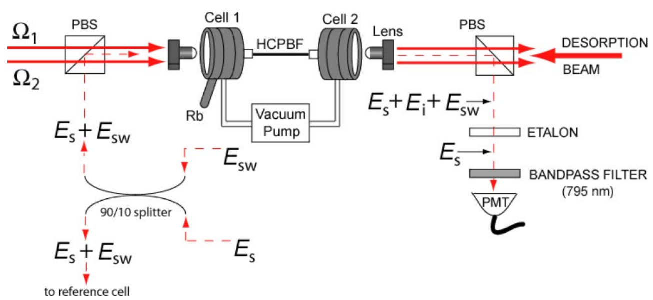

Fig. 2. (Color online) Experimental setup. The switching and signal fields are combined with the pump fields on a PBS. The beams are then focused into the core of the fiber. A counterpropagating desorption beam generates the desired vapor density and optical depth. The modulated signal field is filtered from the pump beams by a second PBS and from the idler and switching fields by an etalon and is then detected with a PMT.

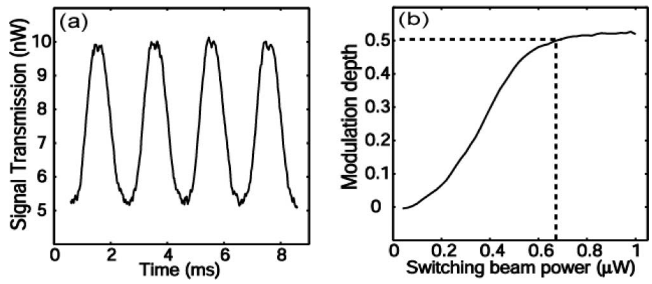

Fig. 3. (a) Modulated signal. FWM modulation at 500 Hz with the signal tuned to the two-photon resonance. The 5 nW signal experiences a gain of 2 with 15 μW of total pump power. We observe 3 dB of attenuation with 1 μW of switching power. (b) Saturation of modulation depth. Signal modulation depth as a function of switching power. Modulation begins to saturate at 0.65 μW.

if there was no FWM, and the idler field is completely extinguished. Figure 3(b) shows the modulation depth observed in the signal as a function of the peak switching power. We find that the modulation depth begins to saturate at 50% for a switching power of 0.65 μW [see dotted line in Fig. 3(b)], and increasing the switching power further does not improve the modulation depth. A slow scan of the signal frequency about two-photon resonance reveals that the modulation is present over the entire FWM gain bandwidth of $\sim$100 MHz, which implies a system response time of 1.6 ns. Taking this response time into account, 50% modulation at 0.65 μW of switching power corresponds to 3600 photons of switching energy or to 23 photons per atomic cross section $\lambda^2/(2\pi)$

We interpret these results as the consequence of the population cycling on the D2 transition that is induced by the switching beam. This spoils the phase relationship between the ground states and destroys their coherence, which is necessary for performing FWM, within one Rabi cycle. The Rabi frequency corresponding to $\sim$600 nW of switching power on the D2 line is 120 MHz, i.e.. roughly equal to the FWM gain bandwidth. Once there is sufficient power to destroy coherence within the FWM response time, greater switching power no longer increases the amount of modulation, which leads to the saturation behavior seen with respect to switching power.

We also studied the effect of gain/modulation bandwidth B on the modulation depth M for a constant switching field power (see Fig. 4). The FWM gain bandwidth can be modified by changing the relative powers of the two pump fields. In the double-lambda scheme used here, the FWM gain coefficient is proportional to the ratio of the Rabi frequency of the off-resonant pump to that of the on-resonant pump, i.e., to Ω_1/Ω_2. Since the gain bandwidth is proportional to the product of the Rabi frequencies of the two pumps, i.e., $\Omega_1\Omega_2$ [11,15], one can modify the gain bandwidth without changing the actual gain by simply changing the relative pump powers such that $\Omega_1\Omega_2$ varies but Ω_1/Ω_2 maintains its value. Based on this idea, we observe gain/modulation bandwidths up to 300 MHz. It is evident that the modulation depth decreases with increasing bandwidth for a given switching power (circles). We can determine the number of switching photons required for 3 dB modulation of the signal field, i.e., the switching energy, by calculating the product of the switching power required for 50% modulation

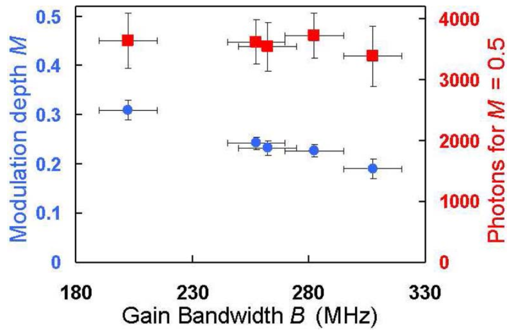

Fig. 4. (Color online) Modulation depth and number of switching photons versus FWM bandwidth. The circles show the modulation depth observed in the signal field as a function of the FWM gain bandwidth. The switching power used for all the measurements was 400 nW. The squares show the switching photon number required for 50% modulation of the signal. The switching photon number is observed to be fairly insensitive to bandwidth. Error bars represent measurement inaccuracy.

($M = 0.5$) and the response time of the system (inverse of the bandwidth), for each bandwidth value B. We see that the number of photons required in the switching field is relatively insensitive to the bandwidth (squares), and the data agree fairly well with the estimated number of 3600 photons.

In summary, we have observed all-optical modulation of FWM using Rb vapor in a PBGF. We observe 3 dB attenuation of the signal beam using only 3600 photons of switching energy or 23 photons per atomic cross section $\lambda^2/(2\pi)$, which is comparable to that achieved in more elaborate cold atom setups [2,3]. Moreover, we demonstrate tunable modulation bandwidths of up to 300 MHz, which is very high for an alkali vapor interaction. These preliminary results show the potential of an Rb-PBGF system for nonlinear optical interactions at a low photon number. For example, it should be possible to enhance important alkali-based quantum-optical interactions, such as QND measurement techniques and the production of squeezed states, due to the tight confinement and high optical depths. One limiting factor in our setup currently is the small transit time (~5 ns) of the Rb atoms across the core of the PBGF, which limits the ground state coherence time. Producing a purer state among the ground hyperfine levels by increasing the transit time through collisions with a buffer gas should improve the results [18–20]. One could also increase the available switching bandwidth by broadening the D2 transition with the injection of a buffer gas into the system.

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