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Super efficient absorption filter for quantum memory using atomic ensembles in a vapor

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Abstract

We demonstrate how a natural rubidium vapor cell can efficiently filter out a pump beam that produces an Raman gain in the stimulated Raman process at the D2 line of ^{85}Rb. We observe a Raman gain of at least 12 dB in ^{85}Rb when the pump beam is detuned below the first transition in ^{85}Rb, while being exactly on-resonance with the first transition in ^{87}Rb. With a single pass through a second cell, we observe an attenuation of at least 30 dB of the incoming pump at 2 mW, while the probe remained unaffected. This filtering process is critical to the realization of a single photon quantum memory based on vapor cells.

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Recently, proposed experimental realizations of quantum memories using halted light can be divided into three categories. They use either Bose–Einstein condensates [1,2], cryogenic solids [3] or vapor ensembles [4]. Similar processes in vapor ensembles have also been proposed to be used for quantum teleportation [5–9]. For the BEC-based memories, the main physical limitation is that the density is too low. In the case of the solid-state experiments, a potentially important constraint is the imprecision in the selection rules. The atomic vapor may be the best compromise, since it does not suffer from these two inconveniences. A possible quantum memory using an atomic vapor would involve sending one probe photon from an entangled photon pair [10] through a vapor cell, and another photon from the same pair through a different path. A pump pulse temporally

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superposed with the probe photon is sent through the memory cell to perform a Raman transition in a Λ system, and store the single photon information in the atomic coherence of the two lower levels of the Λ system. The retrieval operation can be performed by applying a reverse pump pulse. To test the photon storage, the second photon that goes through the second path is sent through a delay line to be compared later with the retrieved photon. We have been investigating the realization of such a quantum memory using rubidium. Our setup is designed to pursue this approach using two natural rubidium vapor cells (25.75% ^{87}Rb and 74.25% ^{85}Rb isotopic concentrations). Our goal is to use the Raman effect in ^{85}Rb vapor to store a single photon [8,12–14] and then to retrieve the photon in a manner that validates the quantum nature of the storage process. In order to detect single photons at the Raman-shifted frequency, one needs to suppress the pump while leaving the Raman-shifted signal intact. The problem of pump suppression is particularly formidable since pump power on the order several hundreds of milliwatts is typically used to produce the Raman effect in the inhomogeneously broadened atomic vapor. Consider for example the case where the stored photon has a temporal duration of 100 ns. For a pump power of 100 mW at 780 nm we need an extinction ratio of about 130 dB. Typically, the pump and probe polarizations are orthogonal, so that a polarizing beam splitter is used to separate them. But the extinction ratio for this process is not good enough. Another potential source of problem is that the pump polarization is modified due to optical activity in the vapor cell [7]. A usual way to filter out one of two very closely separated frequencies is by means of gratings or Fabry–Perot cavities. Gratings are not well suited, because they produce signal scattering. For a filter based on a Fabry–Perot cavity, in order to prevent the concomitant attenuation of the weak field, one would need a very high finesse, such as in the scheme used in [9–11]. Such a cavity requires complicated electronics for stabilization [15]. Furthermore, the transmitted signal is still attenuated significantly, which is highly undesirable in single photon experiments, since it decreases the fidelity of the measurement.

In this letter, we show a serendipitous method to suppress the pump beam very efficiently. In order to illustrate this method it is useful to describe the transitions used in the system. Specifically, we use the hyperfine sublevels of ^{85}Rb for the Λ system. The transitions are illustrated in

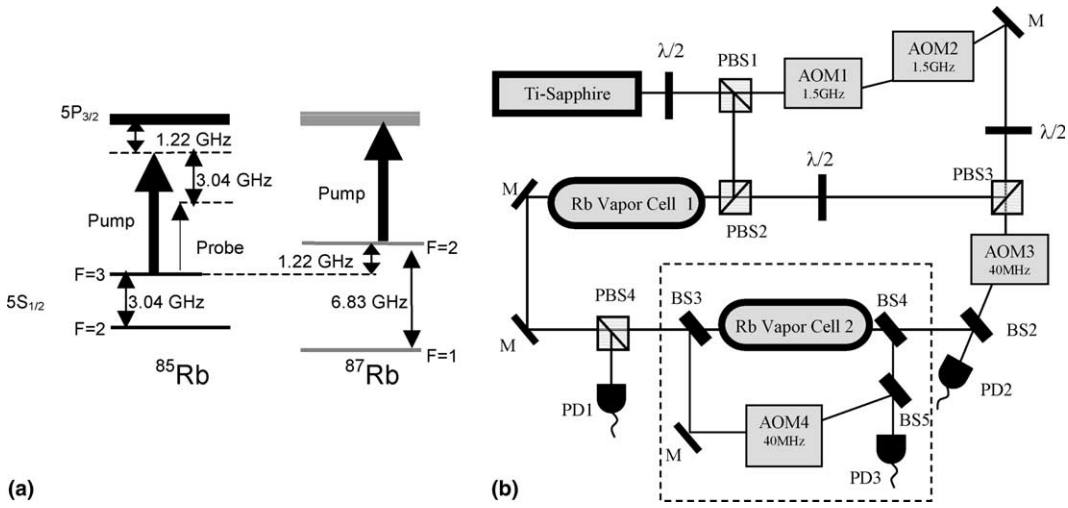

Fig. 1. (a) Energy diagrams in ^{85}Rb and ^{87}Rb isotopes and stimulated Raman process on ^{85}Rb. Notice that the pump field is coincidentally resonant with the ^{87}Rb transition $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$. (b) Experimental Setup. The pump and probe beams are combined at PBS2. The Fabry–Perot cavity is not shown.

Fig. 1(a). Notice that while the probe frequency is always detuned by more than 1 GHz for both rubidium isotopes, the pump frequency happens to coincide with an absorption line of ^{87}Rb. Ordinarily, this is a concern, since this would cause undesirable pump attenuation. However, as described later, we have found that it is possible to observe strong Raman gain under this condition. On the other hand, the presence of this absorption line gives us a naturally occurring filter for the pump, to be realized by a separate cell. In what follows, first we show that the presence of pump absorption does not prevent the Raman gain. Then we show the efficiency of the filter effect.

The use of a vapor cell in general or neighboring isotopic transitions in rubidium in particular for filtering is not new by itself. However, for the objective at hand, the efficiency of the process is not obvious a priori. This is because there is potentially a wide range of detunings that can be employed for the Raman gain process. For example, if one were to use ^{87}Rb transitions, with the pump detuned below the first resonance or above the second resonance, the pump would not be on resonance with any transitions. While absorptive filtering using another cell would still be possible, the attenuation per pass would be rather small, requiring so many passes through the cell that residual scattering and attenuation from the cell windows would become a dominant source of loss for the probe. Even for ^{85}Rb, there are many potential choices of the pump frequency for which the filtering process would be inefficient and ineffective. For example, if trapped atoms were used instead of a vapor cell, the optimal detuning of the pump below the first resonance, which depends on the inhomogeneous broadening of the ensemble, is likely to be less than 1 GHz due to the comparatively negligible Doppler width of the cold atoms. Even for the hot atoms in the vapor, there is no apparent reason to expect that the optimum Raman gain should occur for a pump frequency that is on resonance with the first ^{87}Rb transition. In our experiment, it is accidentally the case that the optimum Raman gain occurs – for a wide range of pump intensities – under precisely this condition. This result also shows that all else being equal (which may not necessarily be the case), one would benefit from using ^{85}Rb as the medium for the quantum memory, as opposed to ^{87}Rb.

The experiment was performed using a Ti:Sapphire laser pumped by an argon-ion laser. Each vapor cell is a heat-pipe oven with a 5-cm active length and a 0.5-cm diameter, containing natural rubidium under a 30-mTorr vacuum maintained by a mechanical pump. As shown in Fig. 1(b), the Ti:Sapphire laser beam is divided by a polarizing beam splitter (PBS1) into two orthogonally polarized beams. We produce the probe beam by red-shifting a part of the pump beam by about 3.04 GHz (corresponding to the ground state hyperfine splitting of ^{85}Rb), using two cascaded 1.52 GHz acousto-optical modulators (AOM), as shown in Fig. 1(b). For diagnostic purposes, part of the probe beam undergoes an additional frequency shift with a 40-MHz AOM (the choice of 40 MHz is due simply to the availability of an efficient AOM at this frequency, and has nothing to do with the fact that the hyperfine splitting frequency happens to be about 40 MHz higher than 3 GHz, of course). The remaining part of the probe is recombined with the pump on PBS2, so that the two co-propagating beams are orthogonally polarized, as required for efficient Raman transitions in this medium. The collimated pump and probe beams are then focused onto the middle of the first rubidium vapor cell with a 50-cm focusing lens. Assuming that the pump beam is Gaussian, its beam spot size is estimated to be 68 μm, and maximum intensity is about 16 kW/cm^2. At the vapor cell output, PBS4 transmits the probe beam and reflects the pump beam. Thus PBS4 filters out most of the pump beam from the transmitted signal, and allows for monitoring the linear absorption in the vapor cell with the photo-detector 1 (PD1). A small amount of the pump that leaks through PBS4 is higher than expected for this PBS. This happens because the pump beam undergoes polarization rotation in the vapor cell due to intensity-induced birefringence in the rubidium atomic vapor. While determining the Raman gain in the first cell, the second cell is kept cold, so that the part of the optical circuit enclosed in the dashed square in Fig. 1(b) does not participate actively in this part of the process. The oven of the first vapor cell is kept at 170 °C. The Raman-amplified probe

is mixed with the 40 MHz-shifted probe on a 50/50 non-polarizing beam splitter (BS2) to give a 40MHz beat signal on PD2. The signal level with the pump blocked is recorded on the spectrum analyzer (Fig. 2(a)). Unblocking the pump increases the beat signal amplitude by 12 dB (Fig. 2(b)). Maximum gain occurs when the Ti:Sapphire laser frequency is detuned 1.22 GHz away from the first ^{85}Rb transition line ($F = 3 \rightarrow 5S_{3/2}$), which coincides with the ^{87}Rb $F = 2 \rightarrow 5S_{3/2}$ transition (Fig. 1(a)). The gain is maximum at the peak pump power mentioned above, and is still observable even when the pump is attenuated by 15 dB. Significantly, the location of the peak gain as a function of pump frequency remains the same over this range of pump powers. The Raman gain decreases gradually when the Ti:Sapphire laser frequency is tuned away from the ^{87}Rb, $F = 2 \rightarrow 5S_{3/2}$ transition. The gain profile as a function of frequency is asymmetric around the peak, as documented previously for the Raman gain process [12–14].

The second cell, operated with its oven at 160 °C, acts as the frequency filter to suppress the residual pump co-propagating with the Raman signal (dashed line inset in Fig. 1(b)). The pump beam is seen to be strongly absorbed in the second vapor cell because it is on-resonance with the ^{87}Rb $F = 2 \rightarrow 5P_{3/2}$ transition line. To verify the absorption levels in spectrally resolved probe and pump, we installed a Fabry–Perot cavity (not shown in the figure) with 95% reflectivity mirrors after the second vapor cell. When the pump frequency is red-detuned by several GHz below the ^{87}Rb $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$ transition, we observe both the pump and the probe in the Fabry–Perot spectrum (Fig. 3(a)). As the laser frequency approaches the ^{87}Rb $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$ transition frequency, the pump signal gradually decreases in the Fabry–Perot spectrum. When the laser is exactly on-resonance with the ^{87}Rb transition, the pump signals is strongly suppressed, while the

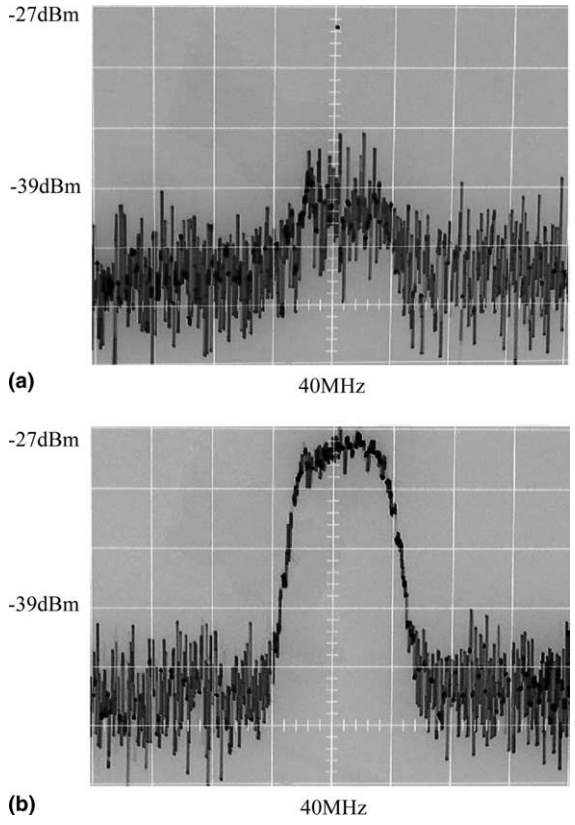

Fig. 2. Stimulated Raman gain. The vertical axis (4 dB/div scale) represents the amplitude of the beat signal of the probe beam going through the cell with the 40 MHz-shifted reference probe. The horizontal axis is on a 5 kHz/div frequency scale. (a) Pump is off. The beating signal peak of 40 MHz is at −39 dBm, or 6 dB above the noise level. (b) Pump is on. The beating signal peak shows a Raman gain of 12 dB as compared to (a).

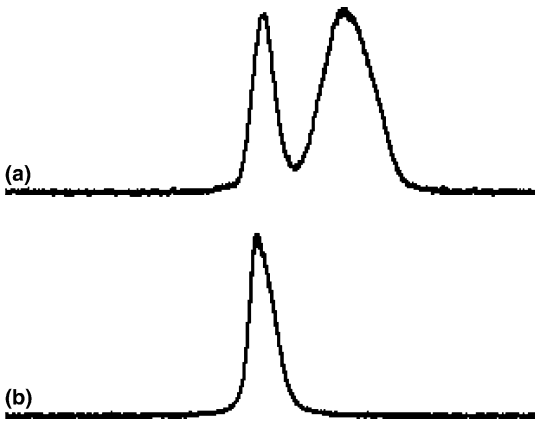

Fig. 3. (a) Pump and probe are spectrally resolved in the Fabry–Perot cavity when the pump is far detuned from the ^{87}Rb $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$ transition. (b) Pump disappears from the Fabry–Perot spectrum when it is on resonance with ^{87}Rb $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$ transition.

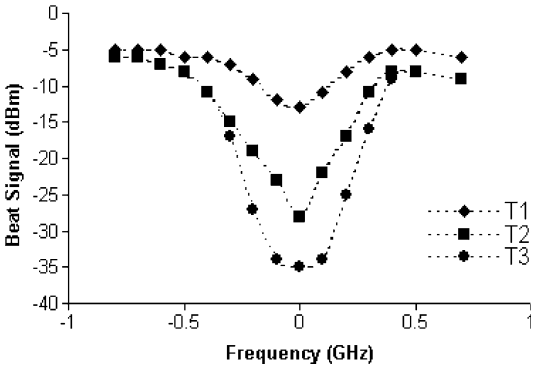

Fig. 4. Absorption increases with increasing oven temperatures ($T_1 = 110$ °C, $T_2 = 150$ °C, $T_3 = 160$ °C). Maximum signal attenuation of 30 dB is observed at the zero frequency, which corresponds to the ^{87}Rb $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$ transition.

probe signal remains unchanged (Fig. 3(b)). Next, we blocked the probe beam (by turning off the 1.52 GHz AOMs), removed the Fabry–Perot cavity and set up a detection scheme to quantify the pump absorption level, starting with the temperature dependence of the absorption (Fig. 4). We split the pump on a 50/50 non-polarizing beam splitter (BS3) just before the entrance to the second vapor cell. Half of the pump beam passes through the second Rb vapor cell, while the other half is frequency-shifted by 40 MHz by AOM4. The beams are recombined on a 50/50 non-polarizing beam splitter (BS5), and the 40 MHz beating signal detected by PD3 is displayed on the spectrum analyzer. When the laser frequency is on-resonance with the first ^{87}Rb transition, the incident pump beam at 2mW is absorbed down to the noise level, or at least by 30 dB. In Fig. 4, we show the absorption profiles as functions of the pump detuning around the ^{87}Rb $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$ transition for different oven temperatures. The maximum pump absorption increases with temperature as expected. We could attain further attenuation by multiple passes through the cell because absorption in this regime is a linear process. The number of passes necessary would be only a few (say 4), so that degradation of the probe from the AR-coated windows would be negligible.

We have demonstrated that the pump beam that produces Raman amplification of the probe of up to 12 dB in ^{85}Rb of a natural Rb vapor cell can be attenuated on a single pass by at least 30 dB with ^{87}Rb of another natural Rb vapor cell, while the probe/signal is not affected. This makes a super-efficient frequency selective filter that may be very useful to simplify single photon experiments involving Raman gains in rubidium vapor.

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