Optically Written Waveguide in an Atomic Vapor

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We present the first demonstration of an optically written waveguide in an atomic vapor. By strongly pumping one rubidium transition, we are able to "waveguide" a weak probe beam at a different rubidium transition. These effects can be understood with reference to a model of the refractive index for a V system. [S0031-9007(99)08495-1]

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In recent years, researchers have shown that light could be used to write a waveguide in a bulk nonlinear medium. Both bright [1] and dark solitons [2,3] have been used to guide light in such media. Potential uses of such all-optical waveguides have already been demonstrated. Luther-Davies and co-workers have shown steering of their optically produced waveguide [4], which may be used to produce an "optical switchyard." Their experiments have also yielded a device that guides a single input beam into two separate beams—a "Y junction" [3]. Morin *et al.* [5] have used a photorefractive spatial soliton to form a waveguide in the bulk of a photorefractive material and have shown that a tapered waveguide improves the guiding efficiency. All of these experiments used solitons, but, in fact, such applications do not strictly require true soliton behavior, as the spreading of a normal beam over a short distance may not be severe.

In experiments in bulk media, the optical frequencies are far from the resonances of the medium, and the effects described above are known as "nonresonant" or "passive" nonlinearities. Similar nonlinear effects have been studied in atomic gases, where the origin of the effect is the nonlinear refractive index arising from saturated absorption [6]. These nonlinear optical phenomena are known as "resonant" or "dynamic" nonlinearities.

It is well known that resonant optical nonlinearities can also cause self-focusing and defocusing effects [7,8], which can result in spatial solitons [9,10] and other interesting spatial patterns [11,12]. While the production and behavior of solitons in atomic vapor have been extensively studied, waveguiding of light by such solitons, analogous to that observed in bulk media, has yet to be reported.

In this paper we describe a novel "waveguiding" experiment, in which a weak probe beam tuned near one atomic resonance is guided through a waveguide written by an intense pump beam at a different atomic resonance, in an atomic vapor. As the pump beam is tuned close to resonance, it creates a nonlinear refractive index profile in the atomic vapor with which the weak probe beam interacts. The probe wavelength is close to the rubidium D_2 line (780 nm, $5^2 S_{1/2} \rightarrow 5^2 P_{3/2}$), while the pump wavelength is close to the rubidium D_1 resonance (795 nm, $5^2 S_{1/2} \rightarrow 5^2 P_{1/2}$). The two beams interact because the D_1 and D_2 transitions share a ground state. By creating an intensity profile of the pump beam with peak intensities of over 280 times the saturation intensity of the Rb vapor, we can create a steep-sided refractive index profile for the probe beam that resembles that of an optical fiber. We show that the waveguide effect is not dependent on the beam having solitonic characteristics.

Theoretical model.—We can represent the rubidium D lines as a V system, for the case of a strong pump beam centered on the $1 \rightarrow 2$ transition and a weak probe near the $1 \rightarrow 3$ transition. This does not take into account the hyperfine splitting or Doppler broadening and ac Stark shifts of the rubidium D lines or the relative linewidths of the lasers and atomic transitions, but can still give a representative picture of the physical effects seen in our experiments. The real part of the linear susceptibility of the medium χ, with respect to the weak probe beam is given by

$$\chi' = -\frac{(N_1 - N_3)\mu_{13}^2}{2\hbar\epsilon_0}\frac{\Delta}{\Delta^2 + \Gamma_{\mathrm{eff}}^2} \simeq -\frac{N_1\mu_{13}^2}{2\hbar\epsilon_0}\frac{\Delta}{\Delta^2 + \Gamma_{\mathrm{eff}}^2}, \quad (1)$$

where μ_{13} is the electric dipole moment of the transition, $\Delta = \omega_p - \omega_{13}$ is the probe detuning, Γ_{eff} is the effective linewidth of the $1 \rightarrow 3$ transition, and N_1 is the population density of level 1. Taking $N_1 = N\{1 - (I/I_{\mathrm{sat}})/[2(1 + I/I_{\mathrm{sat}})]\}$ and $\Gamma_{\mathrm{eff}} = (\Gamma_{12} + \Gamma_{13})/2$ [13], where I is the pump beam intensity, I_{sat} is the saturation intensity, and N is the density of Rb atoms interacting with the pump beam, we find the refractive index,

$$n \simeq 1 - \frac{\mu_{13}^2 N_1}{4\hbar\epsilon_0}\left(1 - \frac{I/I_{\mathrm{sat}}}{2(1 + I/I_{\mathrm{sat}})}\right) \times \frac{\Delta}{\Delta^2 + [(\Gamma_{13} + \Gamma_{12})/2]^2}.$$

A probe beam tuned to the red of the resonance (negative Δ) experiences a refractive index greater than unity. However, where the pump beam is intense, the ground state population N_1 will be reduced, causing a local relative decrease in refractive index. Thus intense regions of

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the pump beam will produce a diverging lens effect, or under the right conditions will guide light out of the intense region of the pump beam, for a red detuned probe. This is similar to the self-defocusing that a red detuned beam would experience through self-depletion of N_1. A blue detuned probe (positive Δ) in the presence of strong pumping of the $1 \rightarrow 2$ transition will see a local refractive index maximum in the high intensity spatial region of the pump beam and will tend to be refracted into it. Figure 1 illustrates this effect, for a pump beam with a "doughnut" intensity profile (a Laguerre-Gaussian beam, as used in our experiment). Figure 1 shows the refractive index estimated using this model for a weak probe beam and a pump beam of peak intensity 280 times the saturation intensity I_{sat}, as was the case in our experiment, as a function of radial position and probe beam detuning. It is easy to see that the steep changes in the refractive index at the edges of the high intensity regions, and the flat areas of almost constant refractive index, resemble the refractive index profile of an optical fiber.

This model can be used to roughly predict the phase shift $\Delta\phi = 2\pi(n - 1)L/\lambda$ that a weak probe beam would acquire on passing through a cell of length L containing atomic vapor, in the presence of strong pumping of the ground state. Using parameters similar to our experiment ($L = 0.1$ m, $\Delta = 4$ GHz, $\lambda = 780$ nm, $N = 4.8 \times 10^{18}$ m^{-3}, and maximum intensity of 280 times I_{sat}), the model predicts a relative phase shift of 40π in the highest intensity region of the pump beam. However, the actual phase change is likely to be somewhat smaller than this, due to hyperfine splitting of the ground state and absorption and spreading of the pump beam over the length of the cell.

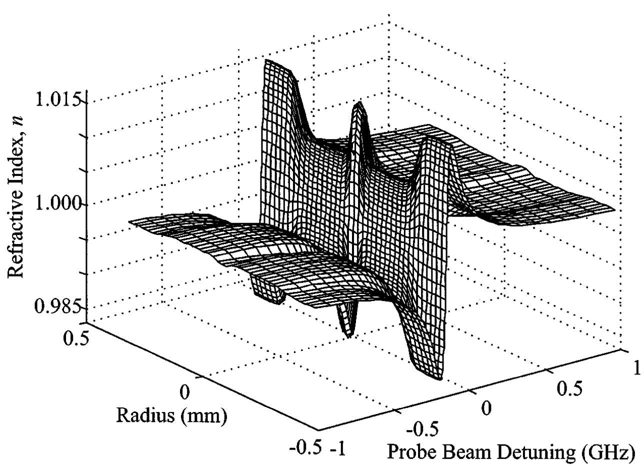


FIG. 1. Theoretical refractive index variations experienced by a weak probe beam in the presence of a strong pump beam. The refractive index profile seen by a weak probe is plotted versus detuning Δ, for a doughnut pump beam of intensity 280 times I_{sat}. On the x axis is the radial variation and the y axis is the variation with detuning. The steep refractive index changes at the edge of the high intensity regions of the beam and the regions of almost constant refractive index resemble the refractive index profile of an optical fiber.

Our use of two Rb transitions sharing a common ground state allows discrimination between the guided and guiding beams, as they are 15 nm apart in wavelength, and the use of two laser frequencies allows us to study both defocusing and focusing sides of resonance by tuning the guided beam frequency through less than 20 GHz.

Experiment and discussion.—The experimental setup is shown in Fig. 2. The waveguiding takes place inside a 10 cm long rubidium vapor cell that contains both ^{85}Rb and ^{87}Rb. The number density of rubidium atoms in the vapor is increased through heating the cell, by wrapping it with a heating element. The equilibrium temperature of the cell for these experiments was 100 °C. The total atomic density N_T is obtained from the relation $N_T = P/kT$, where k is the Boltzmann constant, T is the temperature, and P is the pressure determined empirically [14] by $\log P = 15.882\,53 - \frac{4529.635}{T} + 0.000\,586\,63T - 2.991\,38 \log T + \log(133.322)$, and is 4.7×10^{18} m^{-3} at 100 °C. In view of the strong pumping used we take $N = N_T$.

The laser beam used to write the waveguide was a Laguerre-Gaussian charge 3 doughnut beam, produced by illuminating a computer generated blazed phase hologram [15] with a Ti-S laser. The intensity profile of such a beam is $I = \frac{P}{6\pi}(\frac{2r^2}{\omega(z)^2})^3 \frac{1}{\omega(z)^2} e^{-(2r^2)/[\omega(z)^2]}$, where P is the beam power, $\omega(z)$ is the beam width, and r is the radius. At the input of the cell the doughnut beam power was 400 mW. An external cavity diode laser provided the probe beam of power 10 mW. At this power, at the probe detunings we used for this experiment, no self-action effects of the probe beam were visible. The pump and probe beams were combined using a polarization beam splitting cube, and their powers could be independently adjusted using half-wave plates.

Two lenses were used to bring both beams to a focus. The probe beam was focused onto the entrance window

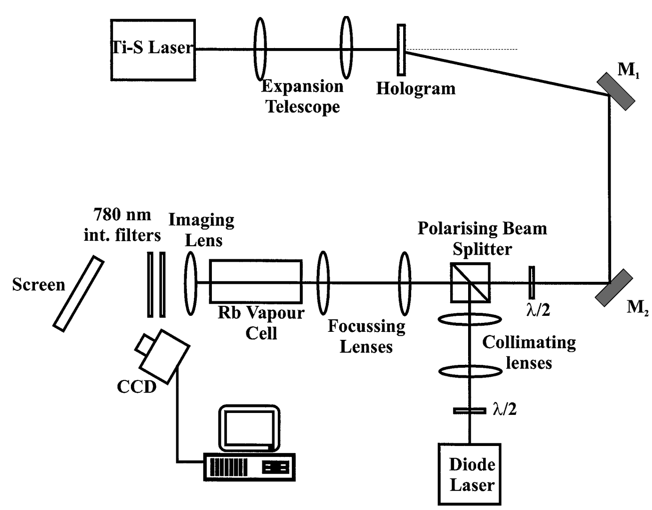


FIG. 2. Experimental setup for guiding of a Guassian probe beam with an optically written waveguide induced by an intense doughnut beam.

of the cell while the doughnut beam was focused into the center of the cell. The waist diameters of the doughnut beam and probe beam were 100 and 40 μm, respectively. For the case of pumping on resonance, this results in a peak intensity in the doughnut annulus of 280 times the estimated saturation intensity. The exit window of the cell was imaged onto a screen and this image was viewed using a CCD camera. Two 780 nm interference filters were used to separate the probe beam from the guiding beam.

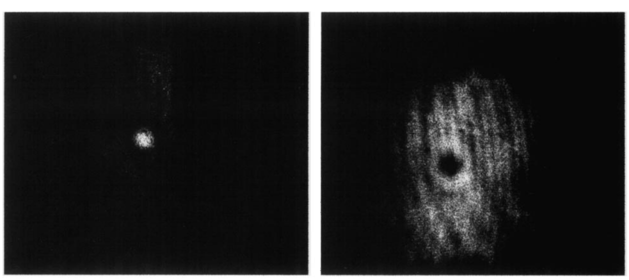
We first set the probe beam frequency to the red of the D_2 (780 nm) resonance of rubidium. The ground state of the D_2 and D_1 lines comprises two hyperfine sublevels for each isotope of rubidium (a total of four), with the total structure spanning 6 GHz. The probe frequency was tuned 2.5 GHz to the red of the longest wavelength D_2 resonance (^{87}Rb $F = 1 \rightarrow F = 0, 1, 2$) of rubidium. By frequency locking the Ti-S laser to an external cavity and monitoring its wavelength using a wave meter, it was possible to scan the frequency of the doughnut beam through the D_1 resonance (795 nm) of rubidium. In this configuration, the red detuned probe beam is always guided into the center of the doughnut beam, as evidenced by the appearance of a bright spot the same size as the dark central spot of the doughnut beam. The guided spot at the output of the cell, shown in Fig. 3a, is much smaller than the probe beam, which has diverged considerably by the time it reaches the output window (the bright area covering most of the frame in Fig. 3b shows the size of the diverged probe beam).

The efficiency with which the probe beam is guided is dependent on the frequency and power of the doughnut beam. With a doughnut power of 400 mW guiding takes place over a 20 GHz frequency range, the highest efficiency being obtained when the doughnut beam is tuned to the longest wavelength of the D_1 transitions. This is expected, as the red detuned probe frequency is closest to the longest wavelength D_2 transition, and the two transitions share a ground state. We found that at least 180 mW of doughnut beam were required to achieve noticeable guiding, which is approximately 126 times I_{sat}. The highest guiding efficiency obtained was on the order of 6% estimated by the ratio of the intensity of the guided spot to the total intensity of the probe beam. We confirmed extinction of the 795 nm guiding beam at every stage throughout these measurements by blocking the 780 nm probe beam, and imaging the guiding beam using the same exposure time. The images shown in Figs. 3 and 4 are of 780 nm light only.

To confirm that we were, in fact, guiding light, rather than merely focusing it onto the exit window of the cell, we changed the angle at which the probe light was launched into our optically written waveguide. We expect that the position of a waveguided beam will not be affected by small changes in the incident beam angle, while a beam that is merely focused will undergo a displacement. Resulting images from this experiment are shown in Fig. 4, and they clearly show the guided spot remaining in the same position while the rest of the beam moves as the incident angle of the probe beam into the waveguide is changed. We conclude that indeed the probe light is being waveguided.

The above experiments were repeated with the probe beam set 3.8 GHz to the blue of the lowest wavelength D_2 resonance of rubidium. In this case, as expected from the refractive index profile, as the frequency of the doughnut beam was varied the probe beam was guided into the bright ring of the guiding beam. The most efficient guiding was found to take place for strong pumping of the ^{85}Rb $F = 3$ ground state. Once again the minimum amount of power required to guide the probe beam was around 180 mW. Figure 3b shows a near field image of the exit window for the most efficient case.

Although we saw some evidence of self-focusing of the pump beam while scanning its frequency through the rubidium resonance, these effects were minimal and at most consisted of a slight change in the width of the doughnut "ring." From this we deduce that in our experiments, the soliton nature of the doughnut beam is not important. However, since we observe guiding when the doughnut beam is in the defocusing regime and we expect that a longer propagation distance would result in the formation



(A) (B)

FIG. 3. Images of the exit face of the rubidium cell. (a) The probe beam is tuned 2.5 GHz to the red of the longest wavelength Rb D_2 line, and the doughnut beam is tuned to pump the longest of the D_1 transitions. The probe beam is guided into the dark center of the doughnut beam. (b) The probe beam is tuned 3.8 GHz to the blue of the shortest wavelength Rb D_2 line, and the doughnut beam is tuned to pump the ^{85}Rb $F = 3$ ground state. Here light is guided into the ring of the doughnut beam, leaving a hole in the original probe beam. In the absence of waveguiding, the probe beam rapidly expands from a waist at the input end of the cell to form a large spot, as shown by the large bright area in (b). The interference effects visible in these frames are due to the interference filters used to separate the two beams.

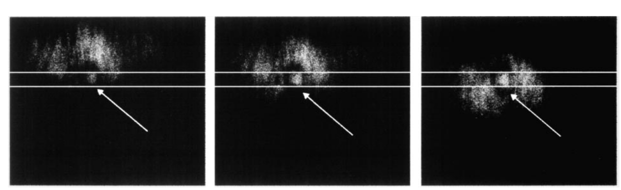


FIG. 4. Images of the exit face of the Rb cell in which the angle at which the probe beam is loaded into the optically written waveguide is varied.

of a dark soliton, it can be assumed that guiding in a dark soliton would occur in that case.

In conclusion, we have shown light guiding light in an atomic vapor. We found the efficiency of the guiding to depend strongly on the power and frequency of the guiding beam. Moreover, since the guiding takes place in an atomic vapor it is possible to tune to both sides of the atomic resonance. This has the distinct advantage that it allows the guiding of light into either bright or dark regions of the guiding beam.

Furthermore, the sensitivity of the output of the waveguide to probe frequency allows for the frequency mode selection of the guided wave. In particular, if one considers a probe beam composed of several oscillating modes separated by many gigahertz, for example, a diode laser, only those modes that are close enough to resonance would be guided.

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