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14. ABSTRACT

In this project, we have been investigating a new approach for manipulating the refractive index of a gas while maintaining vanishing absorption of the beam. We have recently experimentally demonstrated the key ingredients of this approach in Rubidium vapor where we have observe enhanced refractive index with vanishing absorption. We predict that this approach may also allow obtaining negative refraction with low absorption in atomic systems with far-reaching applications in fields as diverse as optical imaging and quantum computing.

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Our project has been funded by the AFOSR since early 2009 through the Young Investigator Program (YIP) Award. We are grateful for AFOSR funding which has been critical in moving the project forward. Our key achievements during this funding period have been:

(i) We have experimentally demonstrated a new approach for increasing the refractive index while maintaining vanishing absorption of the beam [1, 2]. Recently, we have extended this work to short vapor cells and high densities, and demonstrated a relative index of $\Delta n \approx 0.4 \times 10^{-4}$. These experiments were performed at vapor densities exceeding 1.5×10^{14} /cm^3, which is two orders of magnitude larger than alkali densities used in typical electromagnetically induced transparency (EIT) experiments.

(ii) Based on our index enhancement scheme, we have suggested a new approach for negative refraction in atomic systems that utilizes Raman transitions with magneto-electric coupling [3, 4]. Our technique does not require the simultaneous presence of an electric-dipole and a magnetic-dipole transition near the same wavelength. Furthermore, our approach achieves negative refraction with more conservative atomic system parameters compared to previous suggestions. We have also identified suitable transitions in atomic Er and Dy where our technique may be implemented.

(iii) We have experimentally demonstrated a new type of coherent atomic localization with ultracold atoms using the dark state of EIT [5]. With future improvements, dark-state based localization may evolve into a powerful technique for addressing and manipulating atoms at sub-wavelength spatial scales with significant implications for quantum computing.

(iv) We have suggested a new approach for achieving significant nonlinear interactions between two weak beams with energies at the single photon level [6, 7]. Although our scheme does not perform as well as EIT-based approaches in terms of the energy requirement, it is predicted to have significant advantages in bandwidth and robustness.

Below we detail some of these achievements and also summarize future plans.

1 Refractive index enhancement in Rb

It is well-known that a laser beam tuned close to an atomic resonance can experience a large refractive index. However, such a large index is usually accompanied by large absorption. It was first pointed out by Scully [8, 9] that, using atomic coherence, it is possible to obtain a large refractive index with negligible absorption. The pioneering work of Scully was extended to different configurations by Fleischhauer and colleagues [10, 11]. Although these ideas were experimentally demonstrated in a Rb vapor cell by Zibrov *et al.* [12], it has not yet been possible to achieve a large enough refractive index in a vapor to be of practical importance.

Building on these pioneering efforts, our approach utilizes the interference of an absorptive resonance and a gain resonance to obtain an enhanced index with vanishing absorption. As shown in Fig. 1(a), a straightforward way to realize such an interference is to have two different two-level transitions. These two transitions can either be in the same atom or can belong to two different atomic species. In practice, such a multiple two-level scheme has not yet been realized since it is difficult to find two different transitions with close and easily tunable resonance frequencies. Furthermore, due to collisional energy exchange, it is difficult to maintain population inversion in one transition and population non-inversion in the other transition [10]. We recently proposed that

such a multiple two-level scheme can be realized by using Raman resonances in far-off resonant atomic systems [2]. As shown in Fig. 1(b), with an atom starting in the ground state $|g\rangle$, a Raman transition involves absorption of one photon and emission of another photon of different frequency such that the two-photon resonance condition is satisfied. The laser beams that are involved can be very far detuned from the excited state $|e\rangle$. By changing the excitation configuration from the ground level ($E_{c1}E_p^*$ vs $E_pE_{c2}^*$), a Raman resonance can be made amplifying or absorptive for the probe laser. This scheme circumvents the difficulties of the original scheme of Fig. 1(a). The two Raman transition frequencies can be arbitrarily different since we have the freedom to choose the frequencies of the control lasers, E_{c1} and E_{c2}. There is also no population inversion requirement and the system remains mostly in the ground state at all times.

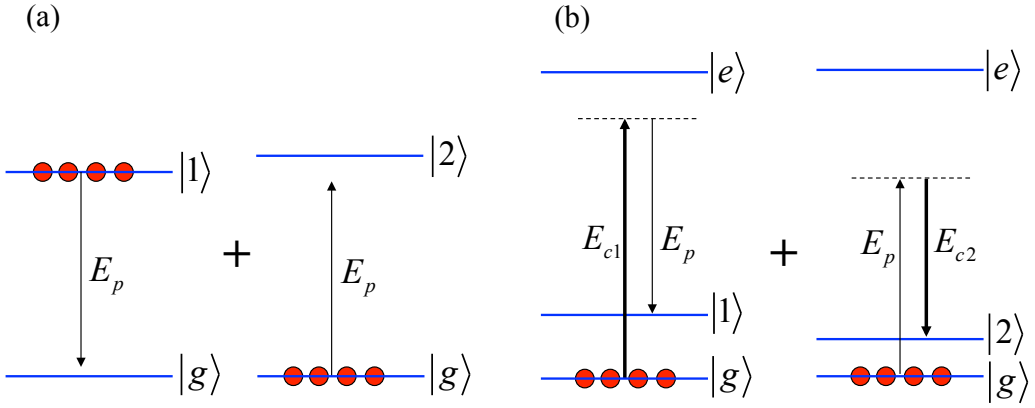

Figure 1: The interference of an absorptive resonance and an amplifying resonance can lead to an enhanced refractive index with vanishing absorption. (a) shows the most straightforward way to achieve such an interference. Due to various difficulties, the scheme in (a) is not practical. (b) shows an equivalent scheme using Raman transitions induced by two control lasers, E_{c1} and E_{c2}. By changing the the excitation configuration from the ground level, a Raman resonance can be made amplifying or absorptive for the probe beam, E_p.

We have recently experimentally demonstrated this effect in a 1-mm-long Rubidium (Rb) vapor cell at high vapor densities. Here, we utilize far-off-resonant Raman transitions between the hyperfine levels of the ground electronic level $5S_{1/2}$. We use excitation through the excited electronic state $5P_{3/2}$ (D2 line) near a wavelength of 780.2 nm. Figure 2 shows the observed gain and absorption resonances as the probe frequency is scanned. Here, we measure the probe intensity absorption or gain at the end of the cell (I_{out}/I_{in}) and then back-calculate the imaginary part of the refractive index using the known cell length. The dashed line is a fit to the gain/absorption data that assumes each resonance to be Lorentzian. The solid line is the calculated real part of the refractive index based on the fits to the imaginary part. By tuning the frequencies of the control laser beams, we can control the position of the Raman resonances as the probe laser frequency is scanned. In plots (a) and (b) the absorption resonance happens before the gain resonance whereas in plot (c) the situation is reversed. As a result, in plots (a) and (b) we observe refractive index reduction with vanishing absorption whereas in plot (c) we observe refractive index enhancement with vanishing absorption. For all three cases, we observe a change in refractive index of $|\Delta n| \approx 0.4 \times 10^{-4}$ with low absorption. The data of Fig. 2 was taken at an atomic density of about 1.5×10^{14} /cm^3, which is about two orders of magnitude larger than typical alkali densities used in EIT experiments.

We are currently working towards extending these results for achieving higher relative indices in our experiment. Calculations predict a maximum achievable relative index of $\Delta n \approx 0.4$ in hot Rb vapor. We also note that ultracold atoms offer unique advantages for studies of refractive

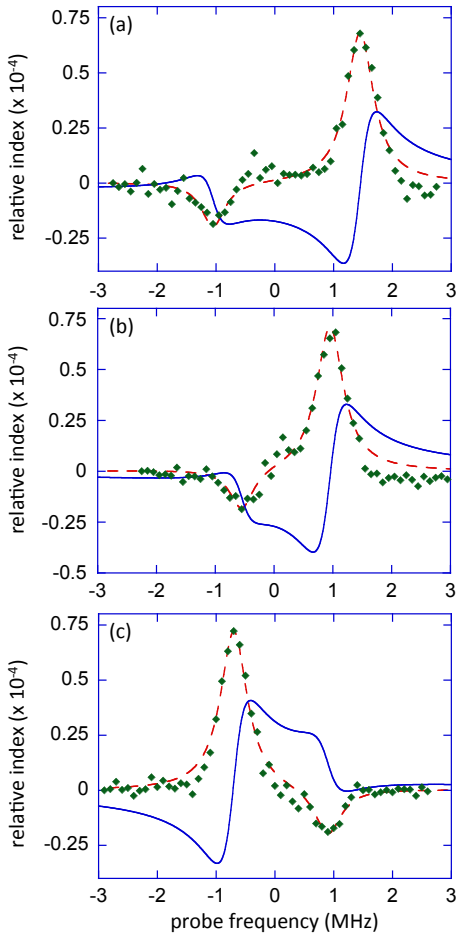

Figure 2: Observation of refractive index manipulation with vanishing absorption. The data points are the observed imaginary part of the refractive index which is deduced from gain or absorption of the probe beam as its frequency is scanned across the resonances. The dashed line is a fit to the data that assumes each resonance to be Lorentzian. The solid line is the calculated real part of the refractive index based on these fits. By varying the frequencies of the control laser beams, we can control the position of the Raman resonances as the probe laser frequency is scanned. In plots (a) and (b) the absorption resonance happens before the gain resonance whereas in plot (c) the situation is reversed. We observe a change in refractive index of $|\Delta n| \approx 0.4 \times 10^{-4}$ with low absorption.

index enhancement. One key advantage is that due to the reduced Doppler broadening, one can work with non-collinear beam geometries. Furthermore, due to greatly reduced excited state and Raman transition linewidths, the required control laser intensities to achieve the maximum possible refractive index is substantially smaller. Due to these advantages, we also plan to study refractive index enhancement with ultracold high density Rb atomic clouds trapped in optical dipole traps. For this purpose, we have recently constructed an optical dipole trap for ultracold ^{87}Rb atoms. We load the dipole trap from a magneto-optical trap (MOT) where we typically trap about one billion ^{87}Rb atoms at a temperature of about 200 microkelvin (μK). The dipole trap is formed by a tightly focused far-off-resonant laser beam where we trap about half a million atoms near the intensity maximum at densities exceeding 10^{12} /cm^3.

2 Negative refraction in atomic systems

The concept of negative refraction, which was first predicted by Veselago more than four decades ago, has recently emerged as a very exciting field of science. In his seminal paper, Veselago argued that materials with simultaneously negative permittivity and permeability would acquire a negative index of refraction, $n < 0$ [13]. Although the interest in these materials remained only a scientific curiosity for a long time, it is now understood that negative refraction may have important and far-reaching practical applications such as constructing perfect lenses [14]. Materials with a negative index of refraction do not exist naturally, and thus they need to be artificially constructed. One approach is to artificially engineer periodic metal-dielectric structures with appropriate electric

and magnetic resonances. These structures, termed meta-materials, typically have a characteristic periodicity scale smaller than the wavelength so that a nearly uniform electromagnetic response is obtained. Recently, utilizing advances in nano-lithography techniques, several groups have reported negative index of refraction at optical frequencies in metal-dielectric nano-structures and photonic crystals [15, 16]. A key difficulty of these experiments, which is particularly pronounced in the optical domain, is the large absorption that accompanies negative refraction. For all experiments that have been performed in the optical region of the spectrum, light is largely absorbed within a few wavelengths of propagation inside the material which is a key limitation for many practical applications.

Our approach utilizes atomic systems that are "artificially" driven with lasers in their internal states so that negative refraction for a weak probe wave is achieved. The key advantages of using driven atomic systems as opposed to meta-materials are: (i) using interference principles, one can obtain a negative index of refraction with negligible absorption, (ii) atomic systems are uniquely suited for achieving negative refraction at shorter and shorter wavelengths, particularly in the visible and ultraviolet regions of the spectrum, (iii) since negative refraction is achieved through manipulation of internal states, the properties of the material can be dynamically modified, opening an array of exciting applications including perfect-lens switches. Despite these key advantages, achieving negative refraction in atomic systems is a very challenging problem and has not yet been experimentally demonstrated due to various difficulties. All recent proposals require a strong electric-dipole and a strong magnetic-dipole transition at almost exactly the same wavelength. It is difficult to satisfy this condition in real atomic systems. Furthermore, achieving simultaneous negative permittivity and permeability requires large atomic densities, typically in excess of 10^{18} /cm^3, which is impractical.

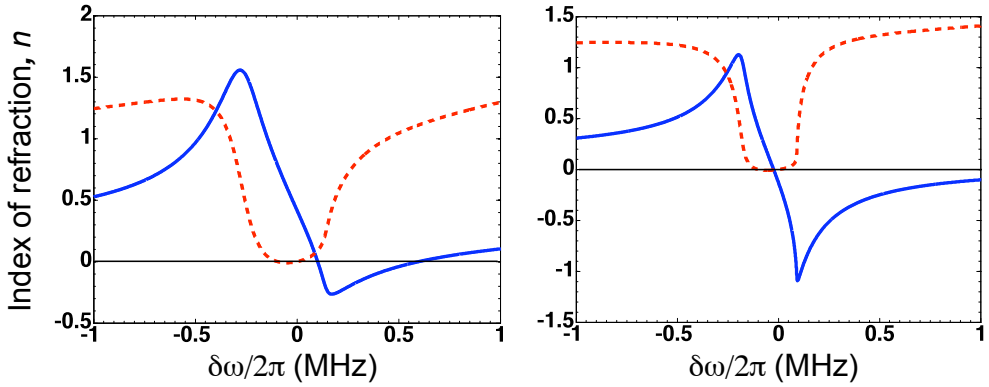

Figure 3: The real (solid blue line) and the imaginary (dashed red line) parts of the index of refraction as the frequency of the probe laser beam is varied for an atomic density of 2×10^{16} /cm^3 (left) and 5×10^{16} /cm^3 (right).

Our approach is predicted to largely overcome these difficulties [4]. To achieve negative refraction with low absorption, we utilize the interference of two Raman transitions combined with magneto-electric coupling (chirality). The key advantage of our approach is that it does not require the simultaneous presence of an electric-dipole and a magnetic-dipole transition near the same transition frequency. This gives considerable flexibility in the energy level structure and may allow an experimental implementation with a number of different species. Furthermore, because of the chiral response, negative refraction does not require negative permeability and can be achieved at much lower atomic densities compared to non-chiral schemes. A detailed discussion of our scheme

can be found in Refs. [3, 4]. Figure 3 shows two representative plots for the real and imaginary parts of the index of refraction that can be achieved using our approach. These plots consider an atomic system where the electric-dipole and magnetic-dipole transition wavelengths may be different by as much as 1 nm. Furthermore, the assumed atomic system parameters (atomic density and transition linewidths) are more conservative compared to other suggestions [17]. As shown in Fig. 3, for a density of 5×10^{16} /cm^3, the index of refraction reaches a value of $n \approx -1$ with low absorption. As discussed in detail in Ref. [3], we have verified the validity of these results by exact numerical calculations of the density matrix.

We have recently been investigating possible experimental implementation of our approach in rare-earth metal atomic species. By using Cowan's atomic structure code [18], we have identified atomic Erbium (Er) and Dysprosium (Dy) as the two most promising candidates. We have found strong and closely spaced electric-dipole and magnetic-dipole transitions in both of these atomic species. As an example, we identified the $4f^{12}(^3H_6)6s^2\ ^3H_6(J=6) \rightarrow 4f^{12}(^1I_6)6s^2\ ^1I_6(J'=6)$ magnetic-dipole transition and the $4f^{12}(^3H_6)6s^2\ ^3H_6(J=6) \rightarrow 4f^{12}(^1G_4)6s6p(^1P_1^o)\ ^1H_5^o(J'=5)$ electric-dipole transition in Er. The wavelengths of these two transitions are in the ultraviolet, and they differ by only 2.2 nm (335.3 nm for the magnetic-dipole and 337.5 nm for the electric-dipole). By using Cowan's code we have calculated the magnetic-dipole reduced matrix element to be $\langle J||\hat{\mu}||J'\rangle = 0.1\mu_B$ (μ_B: Bohr magneton) and the electric-dipole reduced matrix element to be $\langle J||\hat{d}||J'\rangle = 0.2ea_0$ (e: electron charge, a_0: Bohr radius). We have also been investigating possible experimental schemes for implementing our approach with rare earth species. Both Er and Dy have been laser cooled and trapped recently [19, 20]. Furthermore, ultracold atomic densities approaching 10^{15} /cm^3 have been demonstrated in atomic Ytterbium (Yb) [21]. These are very exciting developments, and we feel that high density clouds in optical dipole traps show considerable promise for the studies of negative refraction. Solid state rare-earth doped crystals present an alternative approach for experimental implementation of our technique. Over the next year, we plan to perform detailed theoretical modeling to identify the most suitable atomic species and the experimental approach. The long-term goal is to experimentally obtain negative refraction with low absorption in the optical region of the spectrum.

3 Spatial localization using EIT in ultracold atoms

Over the last decade, quantum computing and quantum information processing have emerged as very exciting fields of science due to the possibility of solving exponentially large problems in polynomial time [22]. A number of implementations of quantum computing, such as those utilizing trapped ions or trapped neutral atoms, use focused laser beams to initialize and manipulate qubits. It is well-known that traditional optical techniques cannot resolve or write features smaller than half the wavelength of light. This barrier, known as the diffraction limit, has important implications for quantum computing. For example, in a neutral-atom quantum computing architecture, the diffraction limit prohibits high-fidelity manipulation of individual atoms if they are separated by less than the wavelength of light. As a result, the qubit spacing must be larger than the wavelength, which limits the two-qubit interaction energies that can be obtained (for example through Rydberg dipole-dipole interaction). The necessary qubit spacing, in turn, limits the fidelity and the speed of the two-qubit gates. To overcome these limitations, it is critical to have a technique that allows addressing and manipulation of qubits in nanometer spatial scales. It has recently been suggested by us [23] and by the Lukin group [24] that sub-wavelength manipulation of atoms or ions can be achieved using position dependence of the dark state of EIT. The key idea is to prepare the atoms to the dark state using a coupling laser with a spatially varying intensity such that atomic excitation can be localized to spatial scales much sharper than the wavelength of light. The

localized excitation can, in turn, be utilized to perform initialization and manipulation of qubits with nanometer resolution.

We have recently reported a proof-of-principle experiment that demonstrated the key ideas of this technique using ultracold Rb atoms trapped in a MOT. A detailed description of this experiment can be found in Ref. [5]. Briefly, we set up an EIT Λ scheme in ^{87}Rb using $|F = 1\rangle \rightarrow |F' = 2\rangle$ and $|F = 2\rangle \rightarrow |F' = 2\rangle$ transitions with the probe and coupling laser beams respectively. The beams have the same circular polarization and the experiment works in three parallel m_F channels. The probe laser has a large beam diameter and overfills the MOT cloud. The coupling laser is split into two beams, which then reconverge at the MOT at an angle of 5 milliradians to form a vertical standing wave. We, therefore, study EIT with a sinusoidally varying coupling laser beam. The experiment starts with all the atoms initialized to the ground $|F = 1\rangle$ level. We then shine the pulsed probe and coupling laser beams each with a duration of a few hundred nanoseconds. To adiabatically drive the atoms to the dark state and establish EIT, we use a counter-intuitive timing sequence, i.e. the coupling laser is turned on before the probe laser beam. With the atoms driven into the dark state, we utilize the sensitivity of the dark state populations to the intensity of the coupling laser beam. Only the atoms that are close to the nodes of the coupling laser efficiently transfer to the $|F = 2\rangle$ level. As a result, the atoms at $|F = 2\rangle$ level can become localized much more tightly than the spatial period of the coupling laser beam. We probe the localization effect by fluorescing $|F = 2\rangle$ level via the cycling transition. The fluorescence signal is detected by an electron-multiplying CCD camera.

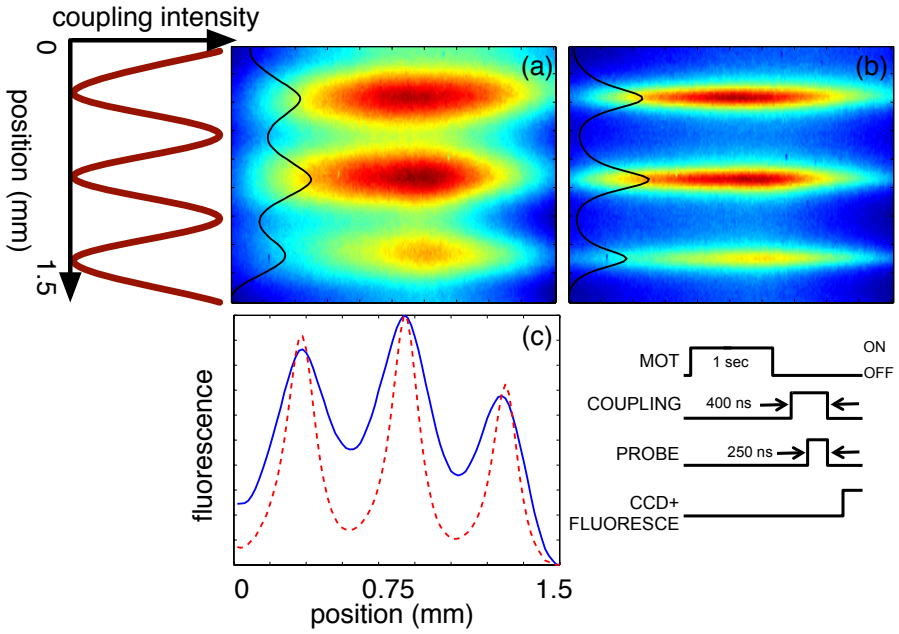

Figure 4: Fluorescence images of the atomic cloud for (a) $I_{C0} \simeq 24 \times I_P$ and (b) $I_{C0} \simeq 460 \times I_P$. The images are obtained by fluorescing the $|F = 2\rangle$ level via the cycling transition after the EIT beams are turned-off. The fringes are confined to the intensity nodes of the coupling beam and become more localized as the intensity of the coupling laser increases. (c) shows horizontally-averaged line profiles of each fluorescence image for more direct comparison. The solid line is for part (a) and the dashed line is for part (b). The lower right diagram shows the experimental timing cycle.

Figure 4 shows two fluorescence images that show localization of the $|F = 2\rangle$ population as the coupling laser intensity is increased. Figure 4(a) illustrates a case where we use a relatively

weak coupling beam, where $I_{C0} \simeq 24 \times I_P$ (I_{C0} is the peak coupling intensity and I_P is the probe intensity). The fringes align with the nodes of the coupling beam intensity and have wide profiles in the vertical dimension. In Fig. 4(b), we use a nearly 20 times more intense coupling laser beam such that $I_{C0} \simeq 460 \times I_P$. We observe the fringes to be vertically much more tightly confined to the control beam nodes. Figure 4(c) shows horizontally-averaged line profiles of each fluorescence image for more direct comparison. The inset in Fig. 4 shows the experimental timing cycle.

We next plan to extend these results to atoms that are trapped in optical dipole traps and demonstrate localization at sub-wavelength spatial scales. If successfully demonstrated, dark state based localization using EIT may provide a powerful tool for adressing and manipulating qubits at nanometer spatial scales and may therefore have significant implications for quantum computing and quantum information processing.

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