

Ultra-dispersive adaptive prism

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We have experimentally demonstrated an ultra-dispersive optical prism made from coherently driven Rb atomic vapor. The prism possesses spectral angular dispersion that is six orders of magnitude higher than that of a prism made of optical glass; it is the highest spectral angular dispersion that has ever been shown (such angular dispersion allows one to spatially resolve light beams with different frequencies separated by a few kHz). The prism operates near the resonant frequency of atomic vapor and its dispersion is optically controlled by a coherent driving field.

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A single frequency ray of light is bent by a prism upon an angle determined by the index of refraction, see Fig.1a. As was shown in [1], the dispersion of the index of refraction leads to spread of deviation angles for different light frequencies.

Optical properties of matter, such as absorption, dispersion, and a variety of nonlinear characteristics, can be manipulated by electromagnetic fields [2, 3, 4]. For example, the applied coherent fields can eliminate ab-

sorption, enhance the index of refraction [5, 6, 7], induce chirality in nonchiral media [8], produce usually forbidden forward Brillouin scattering or strong coherent backward scattering in ultra-dispersive resonant media [9, 10], slow down or speed up light pulses [11, 12, 13], and the optical analog of Stern-Gerlach experiment [14]. Optically controlled giant nonlinearities may generate nonlinear signals using single photons [15, 16]. The enhanced nonlinearity can be employed for quantum information storage [17] and for manipulating of light propagating through a resonant medium, such as stationary pulses of light in an atomic medium [18].

Here we experimentally demonstrate an ultra-dispersive prism (we refer to it as “*a prism*” because it deflects light, see Fig.1b) possessing the highest spectral angular dispersion that has ever been experimentally observed (see Fig. 2,3). The prism is made of a coherently driven atomic Rb vapor [4] that has a spectral angular dispersion ($d\theta/d\lambda = 10^3 \text{ nm}^{-1}$) six orders of magnitude higher than that of glass prisms ($d\theta/d\lambda = 10^{-4} \text{ nm}^{-1}$) or diffraction gratings ($d\theta/d\lambda = 10^{-3} \text{ nm}^{-1}$).

The physics of refraction of the ultra-dispersive coherently driven atomic medium is based on exciting quantum coherence. The wavevector k depends on the light frequency as

$$k = \frac{\omega}{c}n, \quad (1)$$

where n is the index of refraction. Assuming that the driving field has an inhomogeneous profile, then the index of refraction has a spatial gradient. The light ray trajectories in an inhomogeneous medium can be found by solving an eikonal equation [19] given by

$$(\nabla\Psi)^2 = k^2 = \frac{\omega^2}{c^2}n^2 \quad (2)$$

where Ψ is the phase of electromagnetic wave. Then the light turning angle can be estimated as

$$\theta \simeq L\nabla n. \quad (3)$$

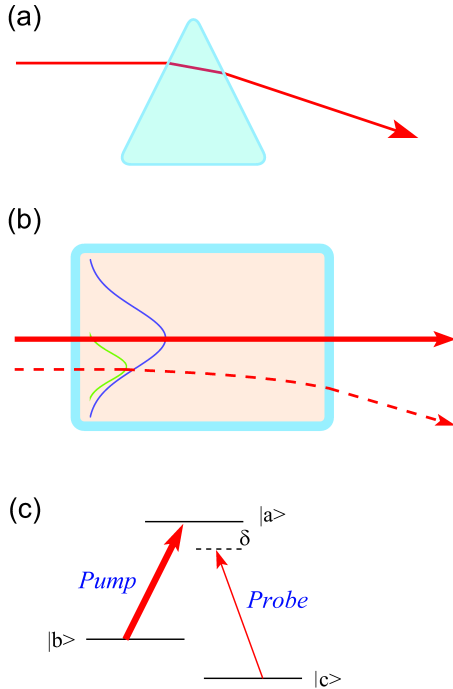


FIG. 1: (a) Refraction of light by the prism. (b) Configuration of the probe and control laser beams inside the cell of Rb vapor. One can see that our setup can be viewed as a super-high dispersive prism. (c) Simplified scheme of the energy levels of Rb atoms.

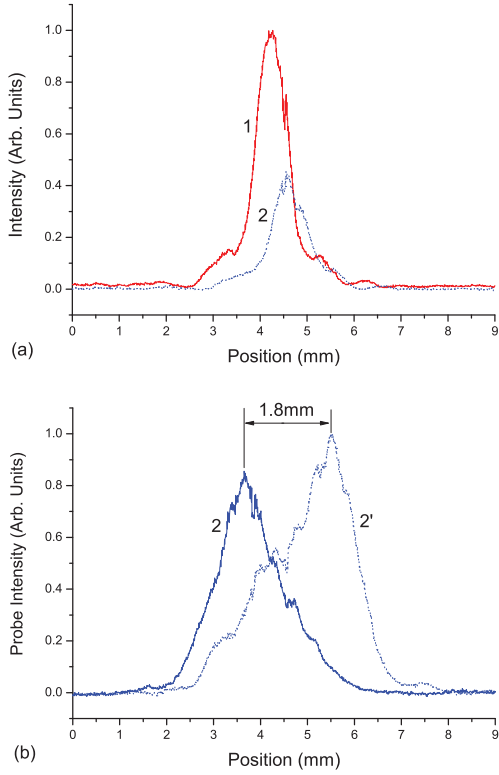


FIG. 2: (a) The spatial distributions of the control (1) and probe (2) fields at the input of the atomic cell. The probe is shifted to the right with respect to the control field. The spatial distributions of the probe fields (2) and (2') at the distance of 2.3 meters after passing the atomic cell for different detunings corresponding to the maximal angles of deviation (see Fig. 3a).

where $n = \sqrt{1 + 4\pi\chi(\omega)}$, L is the length of a medium and $\nabla n(\omega)$ is the gradient of the index of refraction in the direction perpendicular to propagation. The atomic susceptibility of coherently driven medium $\chi(\omega)$ [4] is given by

$$\Re[\chi(\omega)] = \eta\gamma_r\delta\omega \frac{\Omega^2 - \gamma_{cb}^2 - \delta\omega^2}{(\Omega^2 + \gamma_{cb}\gamma - \delta\omega^2)^2 + \delta\omega^2(\gamma_{cb} + \gamma)^2}, \quad (4)$$

where $\eta = 3\lambda^3 N / 16\pi^2$, N is the density of Rb vapor, γ is the relaxation rate at optical transition, γ_{cb} is the relaxation rate at the long-lived lower frequency (spin) transition, Ω is the Rabi frequency of control field, $\delta\omega = \omega - \omega_{ab}$ is the detuning of the probe field from atomic transition $\omega_{ab} = 2\pi c/\lambda$; and λ is the wavelength of resonant transition. Then, for realistic parameters, such as $\delta\omega \simeq 1$ kHz, $\gamma_{cb} = 1$ kHz, $N \simeq 10^{13}$ cm $^{-3}$, $L = 10$ cm the estimate yields $\theta \simeq 0.1$, which shows a lot of potential for implementation of the predicted effect. Note here that the spatial dependence of gradient of the driving field is important, and also that the effect can be increased even more by using an enhanced index of refraction without absorption [5, 6, 7].

The configuration of the laser beams is shown in

Fig.1b, the practical details can be found in [20]. The laser frequency is tuned to the center of the Doppler broadened D₁ line of Rb⁸⁷ (transition $F = 2 - F = 1$). Two orthogonally polarized beams, control ($P_c = 0.5$ mW) and probe ($P_p = 0.5$ mW), create coherence between ground state Zeeman sublevels as shown in Fig. 1c. A heated Rubidium cell ($l = 7.5$ cm, $N = 3 \cdot 10^{11}$ cm $^{-3}$) is installed in a magnetic shield and two-photon detuning is varied by changing the magnitude of a longitudinal magnetic field.

We employ two independent techniques to measure the probe beam position and the angle of deviation. The first technique is based on using a CCD camera and a removable mirror in front of the cell to measure the positions of the control and probe beams. The CCD camera is used to record an optical field distribution for selected two-photon detuning. In the second method, we use a position sensitive detector (PSD) [21] to accurately measure the beam direction versus two-photon detuning. The distance from the center of the cell to PSD is 1 meter and to the CCD camera is 2.3 meters. Measurements by both techniques are consistent with each other.

Before the cell, the control and probe beams are parallel to each other. The probe beam can be adjusted to the left or to the right side of the control beam profile by tilting a parallel glass plate. Then, after the cell, the probe and control beams are not longer parallel (see Fig. 1b). When the probe beam is shifted to the right side, as shown in Fig. 2a, the observed probe beam profiles for two detunings are shown in Fig. 2b. The corresponding dependence of the angles of deviation on detuning is shown in Fig. 3a. The dependence corresponding to the shift of the probe field to the left side of the control field is shown in Fig. 3b. One can see that a different sign of the control field gradient changes the dependence on the detuning.

The width of the probe beam (0.7 mm at the Rb cell) is increased twice at 2.3 meter distance from the cell due to diffraction (the diffraction opening for a Gaussian beam profile is given by $2\lambda/\pi d$, where d is the diameter of the laser beam). For the data shown in Fig. 2b, the displacement due to the ultra prism effect is larger than the spread of the probe beam due to diffraction.

In conclusion, we have experimentally demonstrated a EIT prism yielding large angular dispersion. The obtained results show the dependence of the angle of deviation on the detuning that is introduced by a magnetic field. It follows from Eq.(3), that the angle of deviation is related to dispersion of the medium and the space gradient. Alternating the sign of the spacial gradient by shifting the probe beam, we can see the change of the dependence of the angle of deviation on the two-photon detuning.

The scheme holds promise for many applications. Such ultra-high frequency dispersion could be used for a compact high spectral resolution spectrometer, similar to compact atomic clocks and magnetometers [24]. The prism has a huge angular dispersion ($d\theta/d\lambda = 10^3$ nm $^{-1}$)

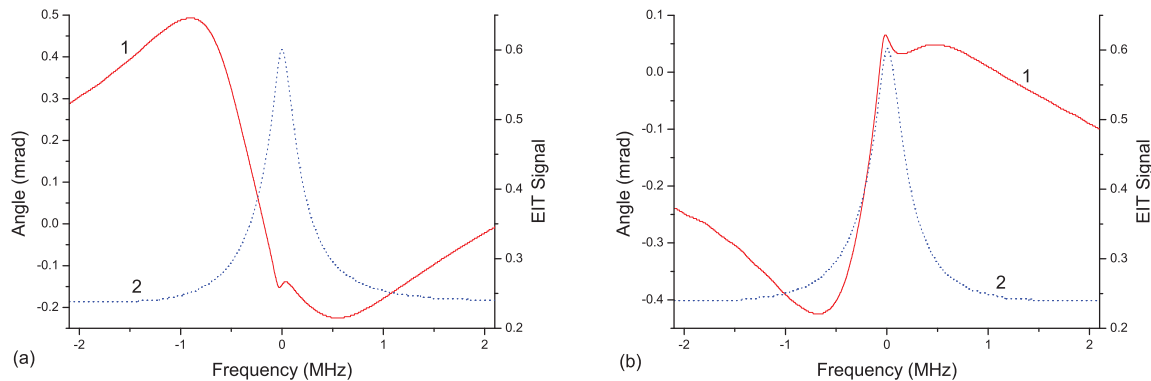


FIG. 3: (1) Dependence of the angle of the probe beam refraction on detuning for the probe beam initially shifted to right (a) and to the left (b) with respect to the control beam. (2) Dependence of the probe field transmission versus detuning.

which can spatially resolve spectral widths of a few kHz (spectral resolution $R = \lambda/\delta\lambda \simeq 10^{12}$). We have observed the angle of deviation to be an order of magnitude larger than the one previously observed in an inhomogeneous magnetic field [14]. We emphasize that the angle can be increased even further by using the enhanced index of refraction without absorption [5, 6, 7].

The ability to control the direction of light propagation by another light beam in transparent medium can be applied to optical imaging and to all-optical light steering [23]. Also, this prism can be used for all-optical controlled delay lines for radar systems. This technique can

be easily extended to short pulses by using the approach developed in [22].

On the other hand, together with application to relatively intense classical fields, the ultra-dispersive prism can have application to weak fields, such as a single photon source, and controlling the flow of photons at the level of a single quanta [15, 16],

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