All-optical switching and routing based on an electromagnetically induced absorption grating

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An electromagnetically induced absorption grating is formed in a three-level atomic vapor under the condition of electromagnetically induced transparency in which the strong coupling beam is replaced by a standing wave. The transmission and reflection behaviors of the weak probe beam are greatly modified at certain frequencies near the two-photon resonance. An all-optical two-port signal router--all-optical switch is demonstrated. © 2005 Optical Society of America

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An electromagnetically induced absorption grating (EIG) can form when a weak probe beam coupled to one atomic transition interacts with a strong standing wave that is coupled to another atomic transition in a three-level atomic system.1 Diffraction of the probe laser beam owing to an EIG was experimentally demonstrated in cold three-level atomic systems.2,3 Recently it was demonstrated that such an EIG in a three-level electromagnetically induced transparency4,5 (EIT) system can be used to store probe pulses in a vapor of rubidium atoms.6 The EIG is formed by spatially modulated absorption regions that are due to EIT (reduced absorption at the peaks of the standing-wave field and high absorption at the nodes) in a three-level atomic medium, which modifies both the transmission and the reflection properties of the probe beam. Actually, the transmission behavior of a weak probe beam under the influence of a strong standing-wave field in a three-level atomic vapor system was studied theoretically long before EIT phenomena became popular.7 This EIG is quite different from the usual four-wave mixing grating, which depends on the third-order Kerr nonlinear index of refraction.8,9

In this Letter we report our experimental investigations of the EIG effect in a three-level Λ-type atomic system in a vapor cell. The reflection and transmission behaviors of the signal (probe) beam are studied with particular attention to their dependence on laser frequency detunings. By making use of the special transmission and reflection properties of the EIG we demonstrate, in principle, a scheme for achieving an all-optical two-port signal router--all-optical switch in such a three-level EIT system, which is an important element in quantum networking with atomic ensemble systems.10

Our experimental system is shown in Fig. 1. The atomic medium is a vapor of natural rubidium. The D1 line of 87Rb at 795 nm is used; here the probe beam couples ground state |1⟩ (5S1/2, F = 1) to excited state |2⟩ (5P1/2, F = 2) with frequency ωp and detuning Δp = ωp − ω21. The coupling laser beam (copropagating for an EIT or a standing wave for an EIG) interacts with the transition between level |3⟩ (5S1/2, F = 2) and level |2⟩ with frequency ωc and detuning Δc = ωc − ω23. The |1⟩ → |3⟩ transition between the hyperfine levels of the ground state is dipole forbidden but has a dephasing rate γ31 owing to collisions and transient time effects.

The probe beam has a power of 100 µW and a diameter of ~0.6 mm inside the vapor cell. The coupling beams are composed of two oppositely propagating beams (copropagating and counterpropagating beams relative to the probe beam propagation) with identical frequency that overlaps the probe beam inside the vapor cell. A standing wave is formed when both coupling beams are present. Each coupling beam has a power of 4 mW, and the two beams have similar diameters of ~1.2 mm. Both coupling beams have the same linear polarization, which is orthogonal to the probe beam polarization. Laser frequency detunings are monitored with a saturation absorption spectroscopy setup along with Fabry--Perot cavities. The coupling and probe lasers are diode lasers with grating feedback, and each has a (half) linewidth of approximately 250 kHz. The rubidium vapor cell is 7.5 cm in length and is wrapped in µ metal to eliminate external magnetic fields. The

Fig. 1. Simplified schematic of the experimental setup: DET1–DET3, photodetectors; EOM, electro-optic modulator; PBSs, polarizing beam splitters; λ/2s, half-wave plates.
temperature of the cell is set to 60 °C.

An EIT is characterized by a spike in probe beam transmission through the vapor cell in a narrow frequency range about the two-photon resonance (Δp, -Δc=0) in the presence of only the copropagating coupling beam. The corresponding one-photon EIT detuning is defined to be δ, where δ=Δp=Δc. A scan of Δp across the EIT resonance shows an absorption reduction of ~50% for δ=0 with a FWHM of ~8.5 MHz [Fig. 2(a)]. Adding the counterpropagating coupling beam creates a standing wave in the effective coupling intensity. Under this condition the probe beam encounters a standing wave in coupling intensity and, therefore, spatial modulation of the absorption that is due to the EIT. This EIG reflects part of the incident probe beam. Furthermore, for the approximate range -10 MHz<δ<+30 MHz, probe transmission is significantly reduced, as shown in Fig. 2(b) at δ=0, which is attributed to spatial interference effects from modulated absorption.7,11 The transmission characteristics observed for other values of Δc (such that δ is outside this range) are basically a superposition of transmission behaviors attributed to separate atomic velocity subgroup selection by the two coupling beams.12,13

To examine the dependence of the reflection efficiency on frequency detunings, we measured the reflection signals as a function of Δp for fixed values of Δc [Fig. 3(a)]. The reflection signal typically reaches maximum amplitude under the same frequency conditions that produce the maximum absorption reduction for a normal EIT (Δp=-Δc). However, a dip in the reflection efficiency appears near Δp=0 for small values of Δc. When |Δc| is increased beyond ~20 MHz, the dip in reflection amplitude diminishes. The reflection efficiency at two-photon resonance is shown in Fig. 3(b), where a corresponding dip in reflection efficiency is seen near δ=0. An asymmetry with respect to δ is also observed where the peak reflection efficiency is achieved near δ=+30. These reflection features are also attributed to the spatial interference that enhances probe absorption for small δ. The dip in efficiency results because the reflected light is also strongly absorbed before it exits the vapor cell.

The EIG-induced reflection signals shown in Fig. 3(a) are caused primarily by the near-stationary atoms, because it is for these atoms that a standing wave in coupling intensity is formed as a result of relative Doppler frequency shifts. The slow atoms considered here are those that remain within the high-intensity regions of the grating, at least as long as the atomic coherence lifetime. The spatial period of the standing wave is λ=π/kc, so the atomic velocities that satisfy this condition are those with |v|≤γλ/2=5.2 m/s, where γ=2π×4.1 MHz is the average coherence decay rate. Assuming a Lorentzian velocity distribution with a FWHM of δν=2×5.2 m/s centered about v=0, the corresponding distribution as a function of effective Δp would have a FWHM of kδν=13 MHz, which is reasonably close to the typical FWHM of the reflection signals of ~10 MHz. The slow atoms are only ~3.5% of the atomic ensemble (at 60°C), which partially explains the low reflection efficiencies in Fig. 3.

The reflected beam is spatially distinct from the incident probe beam by φ=−1° in propagation angle (Fig. 1), which depends on the relative alignment of the three laser beams. This property, along with the reflection and transmission properties for small δ, is harnessed to make a two-port optical signal router that uses cw laser beams, as shown in Fig. 4 for δ=0. In this case the probe beam and the copropagating coupling beam are always present, and the counterpropagating coupling beam is turned on and off by an electro-optic modulator. When the counterpropagating coupling beam is turned off, the EIT allows the probe beam to be transmitted in the forward di-
rection (port one), and there is no reflection. When the counterpropagating coupling beam is turned on, the probe beam is then reflected in the backward direction (port two), and the probe transmission is inhibited. The distinction ratio for the reflected routing signal is high, and switching times of the order of a microsecond were observed. The effective coupling Rabi frequency (which is low in this experiment) and atomic motion are the main limiting factors for the switching speed.

Larger reflection separation angles ($\phi$) might be achievable with a shorter interaction region, larger laser beam diameters, and higher atomic density. However, we would expect increasing $\phi$ to add additional Doppler broadening to the transmitted and reflected signals of the order of $\Delta \omega_D \phi/2$, where $\Delta \omega_D$ is the FWHM of the Doppler-broadened absorption line, and the reflection efficiency would be reduced. The reflection efficiencies achieved here are limited mainly by several technical aspects of the experiment. Primarily, larger coupling beam powers would improve the efficiency. Increasing the coupling beam diameters and improving the uniformity of the beam profiles would enhance the absorption grating and reduce the coherence dephasing rate that is due to transient effects. Both the EIT and the EIG characteristics would be improved by phase locking the probe and coupling lasers and by reducing the laser linewidths. Also, using cold atomic samples would greatly increase the number of atoms participating in writing the absorption grating, and the residual Doppler effect would be reduced. Although the present experimental setup is not ideal, one could significantly increase the reflection efficiencies by making the improvements mentioned above.

In conclusion, we have investigated probe reflection with an EIG in a three-level EIT system and its dependence on laser frequency detunings. It was shown that, by controlling the intensity of the counterpropagating coupling beam, one can use the transmission and reflection of the probe beam to construct a two-port signal router—all-optical switch. The demonstrated all-optical routing and switching could be useful in quantum information processing and for quantum networking proposed in atomic ensembles.

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