Experimental demonstration of optical switching and routing via four-wave mixing spatial shift

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Abstract: We demonstrate the shift characteristics of four-wave mixing (FWM) beam spots which are controlled by the strong laser fields via the large cross-Kerr nonlinearity. The shift distances and directions are determined by the nonlinear dispersions. Based on such spatial displacements of the FWM beams, as well as the probe beam, we experimentally demonstrate spatial optical switching for one beam or multiple optical beams, which can be used for all-optical switching, switching arrays and routers.

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References and links

1. Introduction

In order to develop the next generation of all-optical communication and computing, certain optical elements are essential, such as all-optical switches and routers. There have been several new schemes reported recently to demonstrate, in principle, such all-optimally controlled switching and routing functions [1–3]. A weak beam was used to selectively turn on/off the...
spots in the spatial pattern of a stronger laser beam via cross-phase modulation (XPM) in a two-level atomic medium [1], showing a spatial switching effect. Also, controlling the linear [2] and nonlinear [3] optical absorptions of one laser beam by another in coherently-prepared atomic media was exploited to show all-optically controlled beam switching. Recently, it was shown that a four-wave mixing (FWM) signal beam can be spatially shifted easily by frequency detunings and intensities of the dressing laser beams following a dispersion-like behavior [4]. Such electromagnetically-induced spatial dispersion (EISD) is greatly enhanced same as for the potential architectures for beam address selection and routing in all-optical communication and switching arrays in the current system. Such controllable spatial beam spot shifts can provide and each beam has more than one final states (spatial locations), it is possible to construct locations are studied as functions of experimental parameters. Since there are two FWM beams and each beam has more than one final states (spatial locations), it is possible to construct switching arrays in the current system. Such controllable spatial beam spot shifts can provide potential architectures for beam address selection and routing in all-optical communication and networks.

2. Theoretical model and experimental scheme

![Diagram of energy levels](image)

The relevant experimental system is shown in Figs. 1(a) and (b). Three energy levels from sodium atoms (in a heat-pipe oven of length 18 cm) are involved in the experimental schemes. The pulse laser beams are aligned spatially as shown in Fig. 1(c). In Fig. 1(a), energy levels \( |0\rangle, |1\rangle, |2\rangle \) form a ladder-type three-level atomic system. Coupling field \( E_2 \) (wavelength of 568.8nm, angular frequency \( \omega_2 \), detuning \( \Delta_2 = 0 \), wave vector \( \mathbf{k}_2 \), and Rabi frequency \( G_2 = 5.1GHz \) ) and \( E_3 \) (with \( \Delta_3 = 0 \), \( \mathbf{k}_3 \), \( G_3 = 15.5GHz \) ) connecting the transition between level \( |1\rangle \) and level \( |2\rangle \), which are from the same near-transform-limited dye laser (10 Hz repetition rate, 5 ns pulse-width and 0.04 cm⁻¹ linewidth). The field \( E_2 \) in beam 1 propagates in the opposite direction of the weak probe field \( E_3 \) (wavelength of 589.0nm, \( \omega_3 \), \( \Delta_3 \), \( \mathbf{k}_3 \), \( G_3 = 4.8GHz \) ) in beam 4, as shown in Fig. 1(c), connecting the transition between \( |0\rangle \) to \( |1\rangle \). \( E_2 \) in beam 3 propagates in the plane (yz) having a small angle...
(0.3') with $E_2$. With the phase-matching condition, it generates a non-degenerated FWM (NDFWM) process satisfying $k_{F_2} = k_i + k_j - k'_2$ (called $E_{F_2}$ for the subsystem $|0\rangle \rightarrow |1\rangle \rightarrow |2\rangle$). Then, additional fields $E_1$ ($\omega_1$, $\Delta_i$, $k_i$, $G_i = 5.1\text{GHz}$) and $E'_1$ ($\omega_1$, $\Delta_i$, $k'_i$, $G'_i$) are added, which are from the other dye laser with similar characteristics as the first one, also connecting the transition between $|0\rangle$ to $|1\rangle$. $E_1$ adds onto beam 1 and $E'_1$ (beam 2) propagates in another plane (xz) which is perpendicular to the yz plane with a small angle relative to $E_1$, as shown in the inset of Fig. 1(c). When $E_1$, $E'$ and $E_3$ are turned on simultaneously with blocking $E_2$, $E'_2$, a DFWM process is generated satisfying the phase-matching condition $k_{F_1} = k_i' - k_i' - k_j$ (called $E_{F_1}$ for the subsystem $|0\rangle \rightarrow |1\rangle$) (Fig. 1(b)). Here we define detuning $\Delta_i = \Omega_i - \omega_i$ with the atomic resonant frequency $\Omega_i$. The average powers of the laser beams $E_1'$, $E_2'$, $E_3'$ and $E_3$ are 3, 100, 5, 95 and 0.14 $\mu$W, respectively. The laser beams $E_1$ ($E'_1$), $E_2$ ($E'_2$) and $E_3$ (with diameters of about 0.59, 0.82 and 0.59 mm, respectively) are horizontally polarized.

When $E_1$, $E'_1$, $E_2$ and $E_3$ are all turned on simultaneously, the NDFWM process $E_{F_2}$ and DFWM process $E_{F_1}$ are generated simultaneously. These two generated FWM signals have the same frequency $\omega_{F_1,2} (= \omega_1)$, but propagate in two different directions, which are monitored by a charge coupled device (CCD) camera (Fig. 1(c)). In the experiment, the intensity of laser beams $E'_1$ is about 5 times stronger than the beam $E'_2$, and about 100 times stronger than the beams $E_{1,2,3}$. According to the inset of Fig. 1(c), with cross-Kerr effect, such horizontal alignment of strong dressing field $E'_1$ and $E'_2$ beams induce horizontal shift of NDFWM $E_{F_2}$ and DFWM $E_{F_1}$, respectively [4]. The probe $E_3$ beam is influenced by the combined effect of $E'_1$ and $E'_2$ beams but mainly shifted horizontally by $E'_1$ beam (Fig. 3(a)). Thus, a pair of $E_1$ and $E_{F_2}$ beams can be switched on and off by $E'_1$ beam, while one $E_{F_1}$ beam can be switched on and off by $E'_2$ beam at the same time.

The theoretical description of the spatial properties of the beams $E_{3, F_1, F_2}$ due to self- and cross-Kerr nonlinearities can be given through numerically solving the following propagation equations:

$$\frac{\partial E_3}{\partial z} - \frac{i}{2k_3} \frac{\partial^2 E_3}{\partial \xi^2} = \frac{ik_j}{n_0} (n_2^{SL} |E_1|^2 + 2n_2^{SL}|E_1| |E'_1|^2 + 2n_2^{SL}|E'_1|^2)E_3,$$  

(1)

$$\frac{\partial E_{F_1}}{\partial z} - \frac{i}{2k_{F_1}} \frac{\partial^2 E_{F_1}}{\partial \xi^2} = \frac{ik_{F_1}}{n_0} (n_2^{SL} |E_{F_1}|^2 + 2n_2^{SX}|E_1|^2 + 2n_2^{SY}|E'_1|^2 + 2n_2^{SY}|E'_1|^2)E_{F_1},$$  

(2)

$$\frac{\partial E_{F_2}}{\partial z} - \frac{i}{2k_{F_2}} \frac{\partial^2 E_{F_2}}{\partial \xi^2} = \frac{ik_{F_2}}{n_0} (n_2^{SL} |E_{F_2}|^2 + 2n_2^{SX}|E'_1|^2 + 2n_2^{SY}|E'_1|^2 + 2n_2^{SY}|E'_1|^2)E_{F_2},$$  

(3)

where $k_i = k_{F_1} = k_{F_2} = \omega_{F_1,2} / c$. $z$ and $\xi$ are the longitudinal and transverse coordinates, respectively. $n_0$ is the linear refractive index at $\omega_1$. $n_2^{SL}$ are the self-Kerr coefficients of $E_{3, F_1, F_2}$ and $n_2^{SX, SY}$ are the cross-Kerr coefficients of $E_{3,2}$ and $E'_{1,2}$, respectively. Generally, the Kerr coefficient can be defined by $n_2 = \text{Re} \chi^{(3)} / (\varepsilon_0 c n_0)$, with the nonlinear susceptibility $\chi^{(3)} = D\rho_0^{(3)}$, where $D = N\mu_1^2\mu_2^2 / \hbar^2\varepsilon_0 G_1 G'_2$, $\rho_0^{(3)}(E_{F_1}) = -i G_{F_1} G'_2 / |\eta|$. 

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$\rho_0^{(3)}(E_{F2}) = -iG_{F2} |G_i\rangle \langle \eta|$, $\rho_0^{(3)}(E_i) = -iG_i |G_i\rangle \langle \eta|$, and $\eta = D_i^2 D_2$. $D_{i,2}$ are the parameters related to the Rabi frequency of the dressing field, the frequency detuning, and the atomic coherence rate. $\mu_i$ ($\mu_j$) is the dipole matrix element between the states coupled by the probe beam $E_i$ (between $|i\rangle$ and $|j\rangle$). By assuming Gaussian profiles for the input fields, Eqs. (1)-(3) are solved by the split-step method.

3. Optical switching and routing via spatial shift

Fig. 2. (a) Spatial dispersion curves of $E_{F2}$ in the ladder-type three-level system versus $\Delta_1$ with $G'_i = 52$GHz at 250°C. (b) The spatial displacement of $E_{F2}$ versus $G'_i$ in the ladder-type three-level system at $\Delta_1 = -18$GHz and 250°C. (c) The spatial displacement of $E_{F2}$ versus atomic density $N$ with $G'_i = 52$GHz at $\Delta_1 = -18$GHz. The solid lines are theoretically calculated spatial shifts and the scattered points are the experimental results.

When four laser beams ($E'_1$, $E_2$, $E'_2$ and $E_3$) are on, in the presence of the dressing beam $E'_1$, the spatial shift of $E_{F2}$ beam spot versus probe laser frequency detuning $\Delta_1$ is shown in Fig. 2(a). The moving trace of the light spot is dispersion-like as frequency scans [4]. It means $E_{F2}$ beam can have right or left shift. There are two maximal displacements corresponding to the positive maximum nonlinear refraction coefficient and the negative maximum coefficient. Without $E'_1$ beam, the probe field $E_3$ and $E_{F2}$ are single strong spots, as shown in Fig. 3(a). When the dressing field $E'_1$ is on, the intensities of the probe and $E_{F2}$ beams become weaker [9] and are shifted (one to the right and another to the left of the original position). Since we use one more mirror in the probe beam scheme than that of $E_{F2}$, they have opposite direction of shift on CCD screen (Fig. 3(a)). In fact, in the heated pipe both two beams have right shift, as shown in Fig. 3(b, c). Larger spatial shift occurs with an increasing $E'_1$ intensity, which can be understood from the expression:

$$\varphi_{nl}(z, \xi) = 2k_{\lambda} n_0 I'_1 \exp(-\xi^2) \xi / n_0,$$

The nonlinear phase shift $\varphi_{nl}$ is directly proportional to the dressing intensity $I'_1$. The component of the wave vector of the $E_{F2}$ spot $\delta k_\xi$ (which we use to measure the shift effect of the optical switch) is the derivative of $\varphi_{nl}$, i.e. $\delta k_\xi = \partial \varphi_{nl} / \partial \xi$, so the beam spots also move more as the dressing laser intensity increases.

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Figure 2(b) shows the dressing field dependences of the spatial shifts based on the numerical calculation and the experimental measurements. Figure 2(c) presents the temperature dependence (atomic density $N$) of the shift curves for the theoretical and the experimental results, respectively. We see that increasing the atomic density equals to increasing propagation distance $z$, and the shift of the spot becomes larger.

So, as shown above the beam spots can have different spatial shifts with different experimental parameters (such as frequency, intensity, and atomic density), which can correspond to different on-off combinations. The switching or routing time is the rising and falling times of the switch-in and switch-out signal. The cross-Kerr refractive index change ($n_2 \propto \text{Re}(\rho^{(3)})$) limited by the overall spin dephasing time determines the response time of the switch [3,10,11]. The estimated switching times of $E_{F_1}$ and $E_{F_2}$ are about 32 ns and 400 ns, respectively. Here, it should be noted that the overall spin dephasing times of the two-level (Fig. 1(b)) and ladder-type three-level (Fig. 1(a)) atomic systems in sodium are determined by the transverse relaxation rates: $1/(2\pi\Gamma_{10})$ and $1/(2\pi\Gamma_{20})$, where $\Gamma_{10} = 4.85\text{MHz}$ and $\Gamma_{20} = 398\text{kHz}$ for transitions $|0\rangle \rightarrow |1\rangle$ and $|0\rangle \rightarrow |2\rangle$, respectively. However, the switching speed in Fig. 3 is limited to a microsecond time scale by the speed of the CCD used to take the image.

Figure 3 (a) shows the two states of the probe and $E_{F_2}$ beams by switching the strong laser beam $E'_1$ off and on as the laser frequency detuning is tuned to get the maximal spatial displacement. When a spot stays at its initial position, it means that the switch is in the “off” state. When the frequencies of the probe and $E_{F_2}$ beams are set at their peak shift positions, the light spots will have their largest shifts, so the switch stands at its “on”-state. Such two states form two ports of the optical switch. The upper spot is the $E_{F_2}$ beam and the lower spot is the probe beam. Initially, two spots are set at same vertical line without the dressing laser beam. As the dressing beam $E'_1$ turns on, the upper spot moves to the left side and the lower spot moves to the right side, both of which leave their initial positions completely. The switching contrast can be defined as $C = (I_{\text{off}} - I_{\text{on}})/(I_{\text{on}} + I_{\text{off}})$, where $I_{\text{off}}$ is the light intensity at the
“off”-state and \( I_{on} \) is the light intensity at the “on”-state. The contrast derived from the experiment is about \( C = 92\% \). This experiment provides a physical mechanism to realize an all-optical switching/routing by controlling the dressing laser beam.

A chopper is used to control the dressing field, subtracting the laser pulse repetition time of 0.1s, which is considered as an idle load state. The laser pulse width is 5ns. The detected switching time is limited by the response time of the CCD, which is about 3\( \mu \)s, far larger than the laser pulse width. Thus, the switching speed in the current experiment is greatly constrained as shown in Figs. 3 (b) and (c). The on-state just lasts 5ns, followed by a 3\( \mu \)s rising time, and then a 5ns off-state, followed by a 3\( \mu \)s falling time, and so on. Since the spatial displacements of the probe and \( E_{F2} \) beams are mainly determined and controlled by the large cross-Kerr nonlinear coefficients of the strong laser field \( E'_1 \), the switching speed should be much faster and limited by the atomic coherence time in nanosecond time scale.

Next, when five laser beams (\( E_1, E'_1, E_2, E'_2 \) and \( E_3 \)) are all on, there are interplays between the generated \( E_{F1,F2} \) signals [9] and we can control the shifts of the probe, \( E_{F1} \) and \( E_{F2} \) beams, to achieve a triple binary optical switch. The initial locations of the spots are the “off” states and the switches are considered to come to their “on” states when the spots shift away to new locations. The repetition frequency of the chopper is much longer than 5 ns pulse-width of the dressing laser, so the “on”-state lasts several 5ns intervals and then turns to the “off”-state. In Fig. 4, at \( \Delta_1 = -18\)GHz for the self-focusing side and temperature 250°C, when \( E'_1 \) is on, the probe and \( E_{F2} \) beams have right shift due to the \( E'_1 \) beam via the cross-Kerr nonlinear coefficients. At the same time, the \( E_{F1} \) beam is shifted to the left by the dressing field \( E'_2 \). When \( E'_1 \) is off, all the beams come back to their original position (“off”-state). Since the cross-Kerr nonlinear coefficients \( n_2^{x4} \) and \( n_2^{x6} \) \( (n_2^{x1}) \) of the \( E_{F1} \) and \( E_{F2} \) (probe) beams induced by the dressing fields \( E'_2 \) and \( E'_1 \) are all positive, respectively, the spots of \( E_{F1} \) and \( E_{F2} \) \( (E_1) \) beams are shifted to the opposite directions, as shown in Fig. 4. According to the nonlinear phase shifts \( \varphi_{x1} = 2k_f n_2^{x4} |\alpha|^{\frac{2}{3}} z_0 / n_0 \) and \( \varphi_{x2} = 2k_f n_2^{x6} |\alpha|^{\frac{2}{3}} z_0 / n_0 \) \( (\varphi_{x3} = 2k_f n_2^{x1} |\alpha|^{\frac{2}{3}} z_0 / n_0) \) induced by the dressing fields \( E'_2 \) and

\[ \text{Fig. 4. The switching processes of the dressing beam } E'_1 \text{ (square), } E_{F1} \text{ (triangle), } E_{F2} \text{ (circle), and the probe beam (diamond) in the ladder-type three-level system with } G'_1 = 21\text{GHz at } \Delta_1 = -18\text{GHz and } 250\text{°C.} \]
respectively, we can use two controllable parameters, i.e. the frequency and intensity of the laser, to control the different shifts of the three spots. Such simultaneous optical switching for three beams can perform the functions of choosing different addresses in data transmissions and can be used as the optical routings, the multiplexer or all-optical switching arrays for all-optical networks.

In the above discussion, we have controlled the probe, $E_{F_1}$ and $E_{F_2}$, by two dressing fields $E'_1$ and $E'_2$, respectively. In that case, $E_{F_1}'$ and $E_{F_2}'$ are shifted towards the opposite directions (Fig. 4). Actually, such three beams can also be shifted to the same direction when the sign of the cross Kerr-nonlinear coefficient of the $E_{F_1}$ signal is opposite to those of the $E_{F_2}$ (probe) beams at the proper laser detuning. So, each spot can have left and right locations. Including the initial position, every spot has three possible spatial locations. Totally there are $3 \times 3$ controllable spatial positions. It can such achieve a switch array.

The advantages of solids include high density of atoms, compactness, and absence of atomic diffusion, but with relatively broad optical linewidths and fast decoherence rates. However, there are still many advantages to study all-optical switching, especially spatial all-optical switching and routing, using multi-level atomic media via EIT (or atomic coherence) related effects. The current atomic experiment has several easily tunable experimental parameters (such as laser intensities, frequency detunings, and atomic density), which provide a much better platform (compared to the solid systems) to study the formation and dynamics of the novel spatial optical switch and router protocols. Also, there is a narrow linewidth (compared to the solid systems) in an atomic media.

4. Conclusion

In conclusion, we experimentally demonstrated the spot shifts of the FWMs and probe laser beams, which can be used as the “on” and “off” states of the spatial all-optical switch. Several experimental parameters (such as frequency detunings, intensities and temperature) have been used to optimize the beam shift distances and directions, so the extinction ratio for the on/off states can be optimized. At the same time, the opposite-direction shifting has been realized simultaneously for different FWM beams, which could be employed to construct switching/routing arrays. The current experiment also opens the door for spatial manipulations of FWM signal beams in optical imaging storage [12], quantum correlation [13], all-optical computation, and future all-optical networking.

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