Fast, optically controlled Kerr phase shifter for digital signal processing

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We demonstrate an optically controlled Kerr phase shifter using a room-temperature ^{85}Rb vapor operating in a Raman gain scheme. Phase shifts from zero to π relative to an unshifted reference wave are observed, and gated operations are demonstrated. We further demonstrate the versatile digital manipulation of encoded signal light with an encoded phase-control light field using an unbalanced Mach–Zehnder interferometer. Generalizations of this scheme should be capable of full manipulation of a digitized signal field at high speed, opening the door to future applications.

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The ability to directly control the slowly varying phase of a signal wave by various gated operations is of central importance to any information technologies, such as optical telecommunications and quantum information science. Recently, enhanced Kerr nonlinearity via weakly driven electromagnetically induced transparency (EIT) [1] has been pursued by various groups. This steady-state nonlinear Kerr phase shift scheme [2], which is based on cross-phase modulation of the signal field, achieves the enhancement of the Kerr effect by significantly reducing the propagation velocity [3] of a signal carrier field (often called a probe field). Such schemes, and their variations, which are enhanced by slow signal-propagation velocities have been tested experimentally [4, 5] and a phase shift up to ≃43° has been observed. The fundamental issues with weakly EIT-driven Kerr phase shifting schemes, beyond the fact that they lack tunability, are their inherently slow response time and high loss characteristics. Until recently it was widely believed [3] that the large nonlinear Kerr phase shift required for a nonlinear phase-gate operation could only be achieved when the signal wave propagated ultra slowly, and only in the context of a weakly driven EIT scheme.

In this Letter, we report a proof-of-principle experiment using the active Raman gain (ARG) scheme proposed by Deng and Payne [6]. We demonstrate a fast [7], all-optical, nonlinear Kerr phase shift of a signal field. Contrary to weakly driven EIT schemes that operate in an *absorption* mode, the signal field in an ARG scheme operates in a stimulated Raman *emission* mode. It is precisely this emission mode that gives the signal wave novel propagation characteristics and properties [6, 8]. In the experiment reported here, a signal wave can acquire a fast and yet continuously controllable zero to π phase change, suffer no distortion or attenuation (the signal actually has a small gain), and yet travel with a *superluminal* group velocity (therefore rapid device transient respond time). To the best of our knowledge, to date, no EIT-based Kerr phase scheme can achieve these milestones.

The working medium used in our experiment consists of ^{85}Rb atoms in a magnetically shielded, temperature-controlled (340.6 K) 25 mm diameter vapor cell of length 75 mm (see Fig. 1a for experimental setup). We first empty the population in the $|3\rangle = |5S_{1/2}, F = 3\rangle$ state using a linearly polarized optical-pumping laser (E_{OP}) at 780 nm. After the optical-pumping light is extinguished we turn on a linearly polarized pump laser field (E_P) at wavelength of 795 nm (8 mW with a 5 mm beam diameter). This laser drives the $|1\rangle = |5S_{1/2}, F = 2\rangle \to |2\rangle = |5P_{1/2}, F' = 2, 3\rangle$ transitions with a large positive

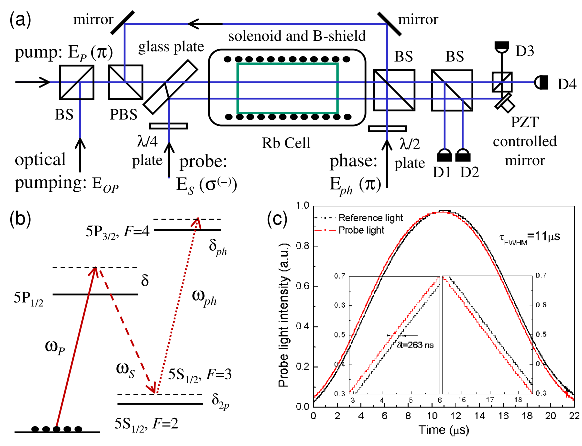

Fig. 1. (a) Experimental setup, (b) energy diagram and laser couplings, and (c) typical signal wave propagation characteristics. The ^{85}Rb vapor cell is shielded from the ambient magnetic field and is also actively temperature controlled. A weak (10 μT) axial magnetic field generated by the solenoid provides a quantization axis for the atoms. Typically, the "superluminal" propagation of a signal field when only the pump and signal fields are present in the medium yields a "lead time" (red curve, from detector D_1) of a few tens to a couple of hundred nanoseconds for a signal light pulse length of about 11 μs when compared to an unshifted reference wave (black curve, from detector D_2).

one-photon detuning of $\Delta/2\pi = 2.1$ GHz. All magnetic substates in the $5S_{1/2}$, $F = 2$ manifold contribute to transitions to the Doppler broadened and overlapped $F' = 2$, 3 manifolds. At the same time a weak (50 μW, 1 mm beam diameter) circularly polarized ($\sigma^{(-)}$) signal field (E_S, wavelength of 795 nm) is also switched on and couples transitions $|2\rangle = |5P_{1/2}, F' = 2, 3\rangle \rightarrow |3\rangle = |5S_{1/2}, F'' = 3\rangle$ with a two-photon detuning $|\delta_{2p}| > \gamma_3$ where γ_3 is the resonance linewidth of the two-photon terminal state $|3\rangle$. In our experiments, $\gamma_3/2\pi \approx 300$ kHz and $\delta_{2p}/2\pi \approx 500$ Hz (Fig. 1b).

We first verified that the signal field propagates "superluminally" in this gain medium with a "lead time" of about 200 ns, in good agreement with what has been reported previously [6, 8–10] (Fig. 1c). Experimentally, we have chosen the one- and two-photon detunings and the pump field intensity to yield an approximate 100 ns "lead time" for the signal field in comparison with a reference signal field that travels within the same temperature-controlled atomic medium but not in the presence of the pump field.

The Kerr nonlinear phase shift of the signal field is induced by a linearly polarized phase-control light field (E_{ph}, wavelength 780 nm, and beam diameter 3 mm) that couples transitions $|3\rangle = |5S_{1/2}, F'' = 3\rangle \rightarrow |4\rangle = |5P_{3/2}, F''' = 4\rangle$ with a small detuning $\delta_{\mathrm{ph}}/2\pi \approx +100$ MHz. Due to Doppler broadening, all $F''' = 2$, 3, 4 manifolds contribute. We measure this phase shift by comparing the phase of a 6 μs signal field in the presence of phase-control light with a reference signal field in the absence of phase-control light. This unbalanced Mach–Zehnder interferometer generates an interferogram when the voltage of the piezo-actuator-controlled mirror is changed. In our experiment, by changing the intensity of the phase-control light field, we can change the phase shift from zero to π as fast as our light modulation apparatus and detectors allow. When the Kerr phase shift reaches π we have observed a nearly complete cancellation of the signal light field at the output

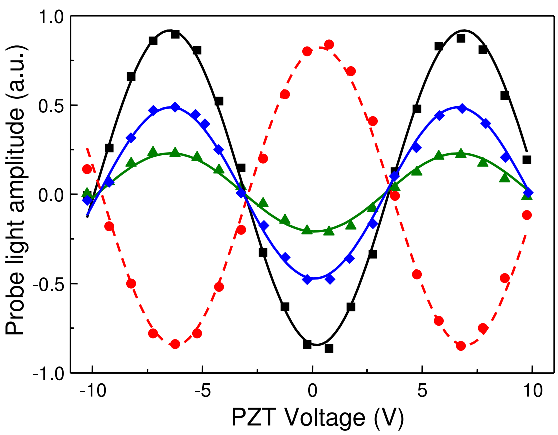

Fig. 2. Mach–Zehnder interferogram showing ψ Kerr nonlinear phase shifts under three different signal light intensities. The dashed curve is the reference. The phase-control light is held fixed in all three cases, and the piezo-actuator control voltage is scanned to capture more than one period and the data fit using a sine function. Upper, middle, and lower solid curves were obtained with signal intensities of 50, 25, and 10 μW, respectively, indicating that the Kerr phase shift is insensitive to the intensity change of the signal laser.

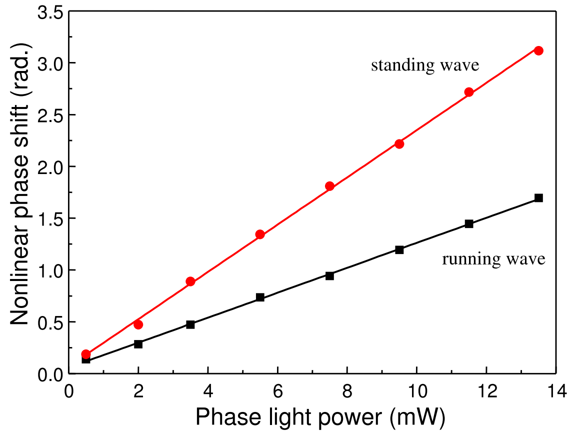

Fig. 3. Plot of Kerr nonlinear phase shift of E_p as a function of the power of the phase-control field E_{ph}. Parameters used are the same as in Fig. 2.

of the Mach–Zehnder interferometer. In Fig. 2 we show typical Kerr phase shift measurements using the unbalanced Mach–Zehnder interferometer. The data are fitted using a sine function to determine the phase difference. Here, we chose the phase-control light intensity to produce a π shift and then held this phase-control light intensity constant and varied the intensity of the signal light. The red dashed line (red dots) is the reference where no phase-control light is present. Three solid lines (black squares, blue diamonds, and green triangle) represent three different signal light powers (50, 25, and 10 μW) with the same phase-control light power fixed for a π phase shift. No detectable phase deviation from π for different signal light powers is a testimonial that the phase shift is independent of the power of the signal field, indicating that the system will work even when the signal light is at the single-photon level [6].

In Fig. 3 we show the Kerr nonlinear phase shift as a function of the phase-control light power for two phase-control field propagation schemes. The black line (black squares) represents the Kerr nonlinear phase change in a running wave set up where the phase-control light copropagates with the signal light. The red line (red dots) represents the Kerr nonlinear phase shift when a standing wave is established in the medium by two counterpropagating phase-control light beams. The factor of two increase of the slope is due to the quadrupling of the intensity in the antinodal regions and the corresponding lack of intensity in the nodal regions.

It should be emphasized that in any EIT-based nonlinear phase shift scheme, the signal field, which is operated in an absorption mode, suffers a significant loss in the quest of a large phase shift and often an additional signal-amplification stage is needed. It is precisely because of this absorption mode operation that an EIT-based scheme does not benefit from an increase in either the density or the propagation distance. Indeed, the figure of merit, which is defined as the ratio of the total phase shift to the total third-order absorption loss [2], is independent of the medium density and propagation length. Such a restriction does not occur in the case of the ARG scheme reported here because the signal field is operated in an emission mode. This is a significant advantage of the ARG scheme over the EIT scheme.

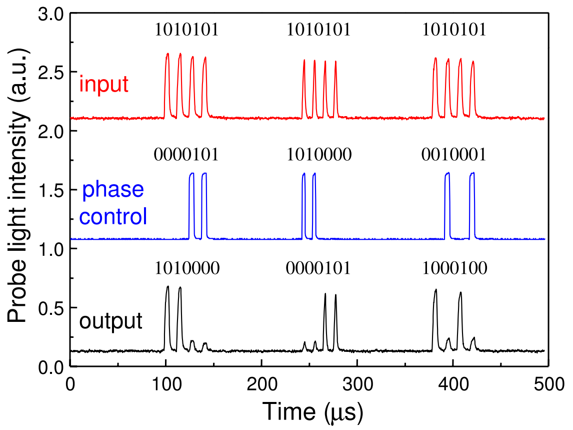

Fig. 4. Demonstration of Kerr-phase-gate-based digital signal control and manipulation. The signal field is encoded with three groups of a fixed digital waveform pattern of 010101010 (top trace). By encoding different digital waveforms to the phase-control laser (middle trace), different output digital waveforms are obtained (bottom trace). In between the groups an additional optical-pumping step was taken due to the two-photon relaxation time.

One of the key requirements of phase-gate operation (or any gate operation for that matter) in telecommunications is the ability to execute fast, reliable, loss-free digital signal processing. In Fig. 4 we demonstrate this capability by executing various digital signal pattern manipulations. In a typical case, we encode the signal field with a fixed digital signal representing 01010101 (top trace), where 0 and 1 represent the absence or presence of a signal light field. By encoding the phase-control light field with various digital forms (middle trace), we observed output in which a cancellation of the signal field peaks can be selectively achieved (bottom trace; residual small peaks are due to small angles between laser beams that lead to nonperfect cancellation). In between each group of digital bits we must execute optical pumping to remove population accumulation in state $|3\rangle$. Technically, there is no difficulty in implementing a much more complex digital waveform as long as the bandwidths of pattern generation components and detectors are sufficient. We note that direct generalization of the scheme reported in this Letter would be a demonstration using engineered materials, such as quantum wells and quantum dots. Phillips *et al.* [11] and Silvestri *et al.* [12] investigated several GaAs/GaAlAs-type quantum-well structures theoretically using schemes analogous to the three-state EIT configuration and demonstrated EIT windows and related characteristics. It is thus reasonable to expect that the Raman gain scheme used in this Letter will behave similarly, but better simply because the large off-resonance operation significantly relaxes many of the requirements demanded by on-resonance operation such as with EIT.

In conclusion, we have demonstrated experimentally the first fast, all-optical, zero to π Kerr phase manipulation of a signal light field encoded with digital information. Using an unbalanced Mach–Zehnder interferometer we have shown a phase-control-light-induced continuous change of the slowly varying phase of a signal field. In particular, we demonstrated a complete cancellation of the signal field by inducing a π phase change. By encoding the phase-control field with digital control sequences, we demonstrated continuous manipulation of the digital signal encoded on the signal field. In essence, we have demonstrated a fast, all-optical, classical-bit, controlled NOT gate. The scheme and experiment reported here may be transplanted and applicable to silicon or polymer-based waveguide systems and technologies, which, if successful, may find wide applications in photonics device engineering.

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