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 85Rb 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 enhanced Kerr nonlinearity via weakly EIT-driven Kerr phase scheme [1]. The working medium used in our experiment consists of 85Rb atoms in a magnetically shielded, temperature-controlled (340.6 K) 25 nm diameter vapor cell of length 75 nm (see Fig. 1a for experimental setup). We first empty the population in the |3⟩ = |5S1/2, F = 3⟩ state using a linearly polarized optical-pumping laser (EOP) at 780 nm. After the optical-pumping light is extinguished we turn on a linearly polarized pump laser field (EP) at wavelength of 795 nm (8 mW with a 5 mm beam diameter). This laser drives the |1⟩ = |5P1/2, F′ = 2⟩ → |2⟩ = |5F1/2, F′ = 2, 3⟩ transitions with a large positive 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 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 enabled 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 [2] 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.

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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 $\mu$W, 1 mm beam diameter) circularly polarized ($\sigma^-$) signal field ($E_s$, wavelength of 795 nm) is also switched on and couples transitions $|2| = |5P_{3/2}, F' = 2, 3 \rangle \rightarrow |3| = |5S_{1/2}, F'' = 3 \rangle$ with a two-photon detuning $\delta_{2p} > \gamma_3$ where $\gamma_3$ 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 $\delta_{ph}/2\pi \approx 100$ MHz. Due to Doppler broadening, all $F'' = 2, 3, 4$ manifolds contribute. We measure this phase shift by comparing the phase of a 6 $\mu$s 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 $\pi$ as fast as our light modulation apparatus and detectors allow. When the Kerr phase shift reaches $\pi$ we have observed a nearly complete cancellation of the signal light field at the output 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 $\pi$ 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 $\mu$W) with the same phase-control light power fixed for a $\pi$ phase shift. No detectable phase deviation from $\pi$ for different signal light powers is a testimonial that the Kerr phase shift is insensitive to the intensity change of the signal laser.

![Fig. 2. Mach-Zehnder interferogram showing $\pi$ 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 $\mu$W, respectively, indicating that the Kerr phase shift is insensitive to the intensity change of the signal laser.](image)
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 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.

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.

References and Note
7. This refers to the latency of the device (i.e., the overall device response time limited by the group velocity of the signal wave), not the light field modulation rate.

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.