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Fast, All-Optical, Zero to π Continuously Controllable Kerr Phase Gate

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We demonstrate a fast Kerr phase gate in a room-temperature ^{85}Rb vapor using a Raman gain method where the probe wave travels "superluminally". Continuously variable, zero to π radian nonlinear Kerr phase shifts of the probe wave relative to a reference wave have been observed at 333^o K. We show rapid manipulation of digitally-encoded probe waves using a digitally encoded phase control light field, demonstrating the capability of the system in information science and telecommunication applications.

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Controlled gate operation is one of the central building blocks of any information technology. The ability to directly control the slowly varying phase of a probe/signal wave is thus of technological importance in information science. In solid-state media such as optical fibers, nonlinear phase shifts can be induced using self- or cross-phase modulation (SPM/CPM)[1] effects. These effects, however, are usually very weak and require an extended propagation distance [2]. In gaseous-phase media, distinct energy levels and selection rules allow strong resonance enhancement [3] of nonlinear effects such as SPM and CPM for sufficiently small detunings. A typical four-level scheme [4] using continuous-wave, weakly-driven electromagnetically induced transparency [5] (EIT) is based on these considerations. This steady-state nonlinear-phase-shift scheme enhances the weak Kerr effect by significantly reducing the propagation velocity of a probe field. This method and its variations have since been used in theoretical studies of quantum entanglement of ultra slow photons [6], single-photon switching [7], Kerr nonlinear phase gates [8], and single-photon propagation control [9]. Several experimental studies [10] based on these investigations using EIT schemes have shown small nonlinear phase shifts using cold atoms. Recently, an EIT-based light-storage/atomic-coherence method [11] has achieved nearly a $\pi/4$ Kerr phase shift with substaintial time delay, and a scheme based on a weak polarizing optical rotation effect [12] has demonstrated a discrete zero or π phase jump.

For any technologically viable Kerr-effect based phase gate four important characteristics must be met. These are fast response, broad tunability, inherently low loss, and controllability. These features, however, are unattainable with weakly-driven EIT-based methods where the probe wave suffers significant attenuation and response times are long. The fundamental problem with weakly-driven EIT schemes is that the process operates in an *absorption* mode, which is inherently slow and lossy. To overcome these difficulties Deng and Payne proposed in 2007 [13] a Kerr phase shift method based on an active Raman gain medium. We note that prior to this theoretical study it was widely believed [6] that only systems exhibiting an ultra-slow group velocity, attainable with a weakly-driven EIT scheme, can result in the large nonlinear Kerr phase shift required for nonlinear phase-gate operations.

In this Letter we report the first fast zero to π continuously controllable Kerr phase gate using a room-temperature active Raman gain medium [13]. In this scheme the probe field operates in a stimulated Raman *emission* mode. It is precisely this emission mode that gives the signal wave novel propagation characteristics and properties [13, 14, 16]. Indeed, we show that the probe wave can acquire a large nonlinear phase shift, suffer no attenuation or distortion (the signal actually has a small gain), and travel with a *superluminal* group velocity (therefore rapid transient times and fast overall device response). Using a Mach-Zehnder interferometer we further demonstrate continuously zero to π phase changes by rapidly modulating the intensity of the phase-control light field. In this manner we can rapidly manipulate the digitally encoded probe field with the digitally encoded phase-control field. This is the first Kerr nonlinear phase gate operation that can meet the key requirements outlined above.

We use ^{85}Rb vapor to demonstrate a continuously controllable Kerr phase gate (Fig. 1). The medium, which is actively temperature stabilized at 333^oK (60^oC), is first optically pumped to the ground state $|1\rangle = |5S_{1/2}, F = 2\rangle$ using a linearly polarized pump laser (wavelength 780 nm) that couples $|3\rangle = |5S_{1/2}, F = 3\rangle$ to the $5P_{3/2}$ manifold. The typical optical pumping time is about 500 μs and we have verified that there is no residual population in the $|3\rangle = |5S_{1/2}, F = 3\rangle$ manifold using a subse-

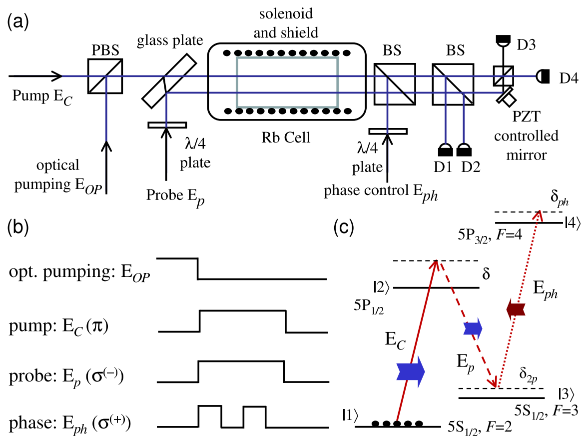

FIG. 1: Experimental setup (a), timing schemes (b), and energy-level diagram with relevant laser couplings (c). The rubidium vapor cell is shielded from the ambient magnetic field and actively temperature controlled at 333^{o}K (60^{o}C). The solenoid provides a weak quantization axis for the atoms using a weak (10 μT) axial magnetic field. In Fig. 1(c), the broad arrows indicate the propagation directions of the light fields.

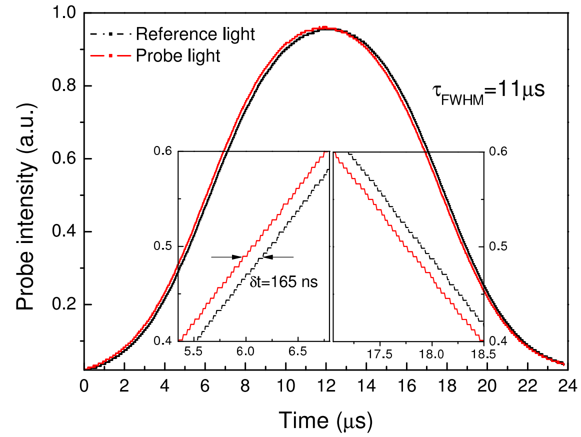

FIG. 2: Typical data showing "superlimunal" propagation of a probe light pulse with a Gaussian time profile with a nominal pulse length of $\tau_{FWHM} = 11\mu$s. We typically choose experimental parameters so that the "lead-time" is about 200 ns when the phase control light field is absent.

quent probe absorption measurement. After the optical pumping light is extinguished, a strong linearly-polarized (10 mW and 5 mm beam diameter) pump laser field (E_C, wavelength 795 nm) is turned on that drives the $|1\rangle = |5S_{1/2}, F = 2\rangle \rightarrow |2\rangle = |5P_{1/2}, F' = 2, 3\rangle$ transitions with a large positive one-photon detuning of $\delta/2\pi \approx$ 2 GHz. All magnetic substates in the $5S_{1/2}, F = 2$ manifold contribute due to the Doppler-broadened overlapping $F' = 2, 3$ manifolds. A weak (50 μW, 1 mm beam diameter) left-circularly-polarized ($\sigma^{(-)}$) probe field E_p couples transitions $|2\rangle = |5P_{1/2}, F' = 2, 3\rangle \rightarrow |3\rangle = |5S_{1/2}, F'' = 3\rangle$ is also turned on so that a two-photon Raman transition is established for state $|3\rangle$ with a two-photon detuning of about 700 kHz. It has been shown both theoretically [13–15] and experimentally [16] that when the two-photon detuning $\delta_{2p} > \gamma_3$ (here γ_3 is the resonance line width of the state $|3\rangle$), the probe field propagates "superluminally". Therefore, this excitation scheme presents a Raman gain medium to the probe field which results in amplification and a superluminal propagation velocity [16]. Experimentally, we have chosen the pump field E_C and the one- and two-photon detunings so as to result in a typical 200 ns "lead-time" in the "superluminal" propagation of the probe field with respect to a reference signal field that travels within the same temperature controlled atomic medium (see Fig. 2). It should be noted that there is a trade-off between the probe gain, the Kerr phase shift, and the "lead-time". To prevent the pump field E_C from entering the detectors we have purposely introduced a very small angle between the pump and probe fields so that they can be spatially separated after propagating the 1 m length of our interferometer arm.

The Kerr phase shift of the probe field is induced and controlled by a circularly-polarized ($\sigma^{(+)}$) phase-control light field E_{ph} (0 to 30 mW with a diameter of 3 mm) that couples the transition $|3\rangle = |5S_{1/2}, F'' = 3\rangle \rightarrow |4\rangle = |5P_{3/2}, F''' = 4\rangle$ with a detuning δ_{ph}. Strictly speaking, the medium is not a simple 4-level system because of contributions from multiple sublevels and transitions (due to Doppler broadening, all $F''' = 2, 3, 4$ manifolds contribute). Because of this consideration, we propagate the phase control light anti-colinearly with respect to the probe light. The phase shift is obtained by comparing the phase of a 15 μs probe pulse using an unbalanced Mach-Zehnder interferometer both with, and without the phase control light field in the two arms. The obtained interferogram is shown in Fig. 3 with a fit using a sine function. Notice that the amplitude of the fit to the data with the phase control light field is slightly higher due to the third-order nonlinear gain, as described in [13].

It has been shown [13] that in the lifetime-broadened 4-level scheme outlined in Fig. 1c that the Kerr nonlinear phase shift $\Phi_{CPM}(\omega_p)$ and the nonlinear gain $G^{(3)}(\omega_p)$ of the probe field by the cross-phase modulation effect per unit propagation length can be expressed as

$$\Phi_{CPM}(\omega_p) = -\kappa_{23}\frac{|\Omega_C|^2}{|\delta|^2\delta_{2p}^2}\left(\frac{|\Omega_{ph}|^2\delta_{ph}}{\delta_{ph}^2+\gamma_{41}^2}\right), \quad (1)$$

$$G^{(3)}(\omega_p) = \kappa_{23}\frac{|\Omega_C|^2}{|\delta|^2\delta_{2p}^2}\left(\frac{|\Omega_{ph}|^2\gamma_{41}}{\delta_{ph}^2+\gamma_{41}^2}\right). \quad (2)$$

Here, $\kappa_{23} = 2\pi\omega_p N D_{23}/(\hbar c)$, where N is the atom concentration and D_{23} is the dipole transition matrix element between the states coupled by the probe field. In

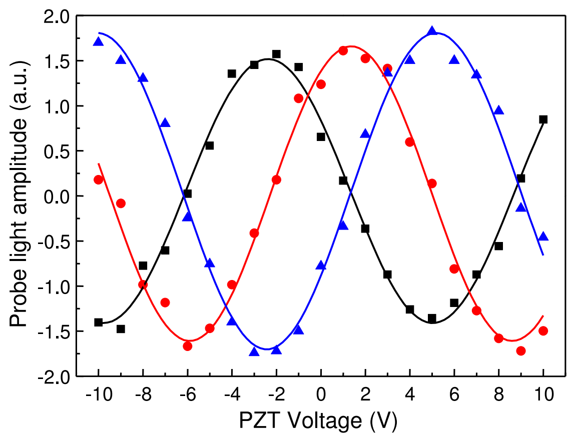

FIG. 3: Typical Mach-Zehnder interferometer output as a function of piezo actuator control voltage for different phase control light powers and fit of the data using a sine function. Phase control light power 0 mW (black squares, non phase-shifted reference), 13 mW (red dots, $\pi/2$ phase shift) and 29 mW (blue triangles, π phase shift). The phase control light is blue detuned by 90 MHz above the $F = 4$, $m_F = +4$ state. As the power of the control light increases, a small third-order Kerr gain to the probe field can be seen (peak-to-peak amplitude increase: 14% and 23% for $\pi/2$ and π phase changes, respectively.

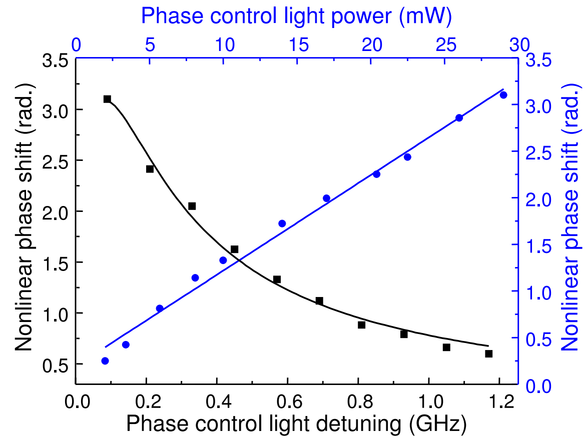

FIG. 4: Kerr nonlinear phase shift as a function of the phase control light power (blue dots, right and upper scales). The phase control light is blue-detuned by 90 MHz above the $F = 4$, $m_F = +4$ state. Kerr nonlinear phase shift as a function of the phase control light detuning (black squares, left and lower scales) for a fixed power of 29 mW. Blue and black solid lines are fits using the function $aP_{ph} + b$ (with a and b being fitting parameters) and $1/\delta_{ph}$, respectively, see Eq. (1).

deriving this result we have neglected γ_{21} and γ_{32} in comparison to the large one-photon detuning δ, and also assumed that the two-photon detuning is much less than the one-photon detuning of the phase control light, i.e., $|\delta_{2p}| \ll |\delta_{ph}|$. Equation (1) indicates that the Kerr phase shift is inversely proportional to the phase-control laser detuning and linearly dependent on the power of this light field. Furthermore, Eq. (2) describes third-order nonlinear *gain*, rather than the usual third-order *attenuation* encountered with weakly-driven EIT-based methods. This is a consequence of the probe wave being operated in a stimulated emission mode [17].

Although Eqs. (1, 2) are obtained for a life-time broadened medium, we expect there to be similar phase control light field dependencies on laser detuning and power even in a Doppler-broadened medium. This is indeed what we have found experimentally. In Fig. 4, we show the phase control light field detuning and power dependence predicted by Eq. (1). Here, we first fix the intensity of the control field and map out the detuning response of the Kerr phase shift using the same interferometric method, the data are found to exhibit the same functional form as Eq. (1). Next, we fix the phase control light detuning but vary the phase laser intensity. As expected from Eq. (1) the Kerr phase shift changes linearly with the phase-control light power.

One of the primary requirements of a phase gate operation (or any gate operation for that matter) in telecommunications is the ability to execute fast (both device respond and modulation rate), reliable, low loss digital signal processing. To demonstrate the advantages, versatility, and capabilities of the Kerr phase gate reported in this work we have executed four and seven digital-signal, pattern-manipulation operations. In the first operation we input a square probe pulse that represents the digital signal 1111 (“non-return to zero”, just a single pulse of a fixed length of 24 μs with each digital 1 lasting for 6 μs). By modulating the intensity of the phase control light field we can create any 4 digit pattern as fast as the modulator allows (about 1 MHz, limited by the modulator we have). Figure 5 shows results from a second operation where digital wave forms of xxxxxxx (x represents 0 or 1) are encoded into the phase control light field to achieve manipulation of the digital signal encoded onto the probe field. In this operation we fix the probe field digital signal as 1010101. There are 4 traces in Fig. 5 and each represents the Mach-Zehnder interferometer output for four digital combinations of the phase control light field intensities. Blue trace: the phase control light is encoded with 0000000 which corresponds to no phase control light, the Mach-Zehnder interferometer faithfully outputs 1010101, which is just the originally encoded probe light. Green trace: the phase control light is encoded with 1111111 which flips the phase of the probe field by π. This causes destructive interference at the output of the Mach-Zehnder interferometer and therefore results in a null output. Black trace: the phase control light is encoded with 0000101 where the two 1’s represent the presence of the π phase-flip operations, yielding the expected output of 1010000. Finally, by encoding

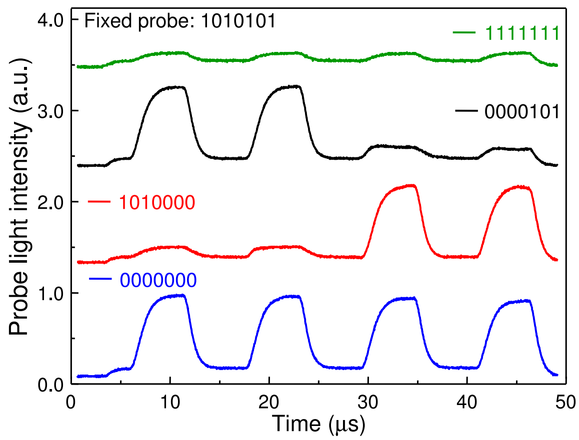

FIG. 5: Demonstration of digital signal manipulation using the Kerr nonlinear phase gate. The probe field digital wave form is fixed as 1010101. There are 4 traces in Fig. 5, representing the digital combination of the phase control light field intensities: 0000000, 1010000, 0000101, and 1111111. Blue trace: the phase control light is encoded with 0000000 and the Mach-Zehnder interferometer faithfully outputs 1010101 (the encoded probe light). Green trace: the phase control light is encoded with 1111111 and the Mach-Zehnder interferometer has a null output as expected. Black trace: the phase control light is encoded with 0000101 where the two 1s represent the presence of π phase-change light, resulting in an output of 1010000. Red trace: By encoding the phase control light with 1010000, the output of the Mach-Zehnder interferometer is 000101. Traces are vertically shifted for clarity.

the phase control light with 1010000, the output of the Mach-Zehnder interferometer is 000101, as shown by the red trace. Technically, there is no difficulty to implement a much complex digital wave form as long as the modulation speed of the various pattern generation components and the corresponding bandwidths of the various modulation and detection elements are sufficient. It should be noted that by modulating the pump field it is possible to achieve full probe-light digital encoding. We emphasize that the scheme demonstrated here is capable of operating at GHz modulation rate or faster (excluding the system preparation time such as optical pumping etc.).

We point out that the theoretical treatment of the Kerr phase gate does not depend on the intensity of the probe field, implying that the formalism can be scaled to the single-photon level. This opens the door to applications in quantum information science. For instance, the Kerr nonlinear phase gate may be implemented together with a controlled-NOT (CNOT) gate based on path-encoded two-qubit operation enabled by two-photon generation in a quantum dot [18]. In addition, it may also be implemented with a Kerr-effect based parity gate [19, 20]. The main challenge, however, is to achieve the direct two-qubit control required for quantum information processing at the single-photon level [21–25]. In this case the phase control laser (reduced to the single-photon level) just becomes the second qubit photon. This is a formidable task and it may require, in addition to a substantial increase in density, the elimination of Doppler broadening of the electronic states (to reduce $|\delta|$ and δ_{ph}) as well as selection of a two-photon state with a much narrower resonance linewidth (to reduce $|\delta_{2p}|$).

In conclusion, we have demonstrated experimentally the first fast, zero to π continuously controllable nonlinear Kerr phase gate. Both detuning and power dependences of the π Kerr phase shift were verified using a Mach-Zehnder interferometer and we have found that the results agree with the functional forms predicted using a life-time broadened atomic system with a similar energy-level structure. We have proven the flexibility of the method by digitizing both the probe and Kerr phase control light fields and manipulating the probe using the digitally-encoded phase control light field. We note that by also encoding the pump field, full-manipulation of the digital signal carried by the probe field can be achieved. We finally note that the fast Kerr scheme reported here may be implemented on wave guide and/or quantum well systems [26] which may find many applications in optical telecommunications.

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[1] R. H. Stolen and A. Ashkin, Appl. Phys. Lett. 22, 294 (1973). M.N. Islam et al., Opt. Lett. 12, 625 (1987). M. Shtaif, Opt. Lett. 23, 1191 (1998).
[2] G.P. Agrawal, *Nonlinear Fiber Optics*, 4th edn., Academic Press, New York (2006).
[3] Y.R. Shen, *Principles of Nonlinear Optics*, 4th edn., Academic Press, New York (1984).
[4] H. Schmidt and A. Imamoglu, Opt. Lett. 21, 1936 (1996).
[5] S. E. Harris, Phys. Today 50, 36 (1997).
[6] M.D. Lukin and A. Imamoglu, Phys. Rev. Lett. 84, 1419 (2000).
[7] S.E. Harris and Y. Yamamoto, Phys. Rev. Lett. 81, 3611 (1998).
[8] C. Ottaviaani *et al.*, Phys. Rev. Lett. 90, 197902 (2003); C. Ottaviaani *et al.*, Phys. Rev. A 73, 010301(R) (2006).
[9] M. Lukin and A. Imamoglu, Nature (London) 413, 273 (2001).
[10] H.S. Kang and Y.F. Zhu, Phys. Rev. Lett. 91, 093601 (2003).
[11] Y.F. Chen et al., Phys. Rev. Lett. 96, 043603 (2006).
[12] R.M. Camacho et al., Phys. Rev. Lett. 102, 013902 (2009).
[13] L. Deng and M.G. Payne, Phys. Rev. Lett. 98, 253902 (2007).
[14] M.G. Payne and L. Deng, Phys. Rev. A 64, 031802(R) (2001) and references therein.
[15] G.X. Huang, C. Hang, and L. Deng, Phys. Rev. A 77, 011803(R), 2008).
[16] K.J. Jiang, L. Deng, and M.G. Payne, Phys. Rev. A 74, 041803(R) (2006).
[17] Unlike the Raman gain method studied here, EIT-based methods are limited by absorption loss. In addition, increasing the density or propagation length with such methods does not increase the phase shift.
[18] M.A. Pooley et al., Appl. Phys. Lett. 100, 211103 (2012).
[19] X.W. Wang et al., Phys. Rev. A 85, 052326 (2012).
[20] K. Nemoto and W.J. Munro, Phys. Rev. Lett. 93, 250502 (2004).
[21] J. Poizat and P. Grangier, Phys. Rev. Lett. 70, 271 (1993).
[22] Q.A. Turchette et al., Phys. Rev. Lett. 75, 4710 (1995).
[23] D. Vitali, M. Fortunato, and P. Tombesi, Phys. Rev. Lett. 85, 445 (2000).
[24] J. Clausen, L. Knoll L, and D.G. Welsch, J. Opt. B 4, 155 (2002).
[25] A. Andre and M. D. Lukin, Phys. Rev. Lett. 89, 143602 (2002).
[26] K.L. Vodopyanov et al., Proceedings of the 8th Int. Symp. “Nanostructures: Physics and Technology”, 153, St. Petersburg, Russia, June 19, 2000.