Realization of an All-Optical Zero to π Cross-Phase Modulation Jump

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We report on the experimental demonstration of an all-optical π cross-phase modulation jump. By performing a preselection, an optically induced unitary transformation, and then a postselection on the polarization degree of freedom, the phase of the output beam acquires either a zero or π phase shift (with no other possible values). The postselection results in optical loss in the output beam. An input state may be chosen near the resulting phase singularity, yielding a π phase shift even for weak interaction strengths. The scheme is experimentally demonstrated using a coherently prepared dark state in a warm atomic cesium vapor.

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The ability to alter the phase of one light beam with another via a nonlinear optical interaction (cross-phase modulation) has potential applications in quantum information [1], precision measurement, optical switching, and other fields. In particular, a cross-phase modulation of π radians is especially useful, since the resulting beam can completely constructively or destructively interfere in a two-mode system. With the aim of achieving a single photon π cross-phase modulation, Schmidt and Imamoglu [2] predicted that a weak Stark shift of a system prepared using electromagnetically induced transparency (EIT) could lead to large cross-phase modulation. Recently, many researchers have studied effects resulting from low-light-level cross-phase modulation based on EIT, including photon switching [3–5], nonlinear optics [6,7], and others. In particular, Braje *et al.* [5] showed that as few as 23 photons per atomic cross section could be used to perturb the dark state sufficiently to destroy the quantum interference leading to EIT for a macroscopic beam.

The amount of cross-phase modulation in these cases is continuous: The resultant phase of the signal may take on any value between zero and 2π. In order to achieve a complete π phase modulation, previous strategies have been to engineer the interaction to generate the required phase change with as few photons as possible. In this Letter, we experimentally demonstrate a cross-phase modulation jump of exactly π radians. This is achieved by creating a phase singularity in an optical field with crossed polarizers as is commonly done in optical metrology [8]. A wave plate placed between the polarizers can cause the phase to flip from 0 to π. In what follows, we replace the wave plate with a weak cross-phase modulation (causing a small rotation) to achieve a phase jump as the small rotation passes through the singularity.

We note that there are a number of other well-known phase singularities in optics. Gouy, for example, showed in 1890 that a focused electromagnetic (or acoustic) wave will undergo a π phase shift by passing through a focus [9], an effect that has recently renewed experimental and theoretical interest [10,11]. Zhou and Cai reported a π phase shift in the output of an interferometer when the relative phase of the optical beams were held fixed at 180° and the amplitude in one arm was varied. A similar effect may be used for edge detection, improved optical readout for data storage, and absolute position measurements [12]. The setup is similar to the process used to measure weak values [13–19]. By preparing the atomic system in proximity to the singularity, a π phase shift may be obtained for a much reduced interaction strength than would be required to achieve a π cross-phase modulation. As in weak value measurements, the primary shortcoming of the present method is the reduction in signal amplitude resulting from postselection.

We first introduce the phase singularity used in the present experiment and then describe an experimental demonstration of an all-optical phase jump in which a signal beam can take on a relative phase of only zero or π, conditional on the presence of a separate beam. Consider a Mach-Zehnder interferometer as shown in Fig. 1, with pre- and postselection on the polarization degree of freedom. Before entering the interferometer, the signal beam passes through a polarizer which sets the input polarization state to be

$$|\psi_1\rangle = |V \pm \Delta\rangle = (-ie^{\mp i\Delta}|+\rangle + ie^{\pm i\Delta}|-\rangle)/\sqrt{2}, \quad (1)$$

where $|H\rangle$ and $|V\rangle$ are horizontal and vertical polarization states, respectively, and $|\pm\rangle = (|H\rangle \pm i|V\rangle)/\sqrt{2}$ are the left and right circular polarizations. The parameter Δ indicates how far away the polarization is from vertical polarization.

The upper arm of the signal beam then passes through an atomic vapor cell that induces a conditional phase shift in the beam, depending on the polarization. Formally, we describe it as a unitary operation U which behaves as

$$U|k\rangle|+\rangle = |k + \delta k\rangle|+\rangle, \qquad U|k\rangle|-\rangle = |k - \delta k\rangle|-\rangle, \quad (2)$$

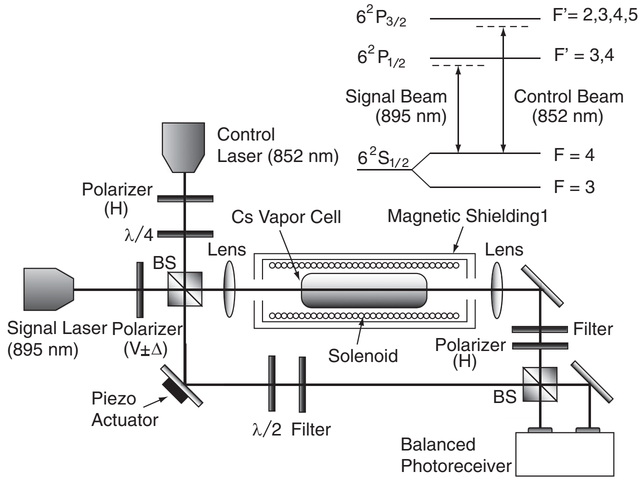

FIG. 1. Experimental setup. A signal beam passes through a polarizer oriented nearly in the vertical direction and then enters a Mach-Zehnder interferometer. In one arm, the signal beam passes through a Cs vapor cell and sets up an atomic dark state among the degenerate ground-state Zeeman sublevels. A separate control laser external to the interferometer (not passed through the two filters shown) perturbs the atomic energy levels, inducing a slight polarization rotation in the signal beam. The signal beam then passes through a second polarizer nearly orthogonal to the input polarizer, which postselects the final state. The phase of the postselected signal beam is then measured by interference at the output beam splitter. The relative phase of the postselected beam is found to take on only the values of zero or π.

where $|k\rangle$ is the momentum basis vector. The propagation within the cell thus induces a phase shift $\phi = \delta k L_{\text{cell}}$ between the left and right circularly polarized states, after which the atom-light interaction ceases, shifting the $|k\rangle$ states back to where they were initially, formally applying the inverse $U^\dagger$.

Being in a coherent superposition, the beam therefore experiences a slight shift ϕ in the polarization of the beam

$$|\Psi\rangle = [\sin(\mp\Delta + \phi)|H\rangle + \cos(\mp\Delta + \phi)|V\rangle]|k\rangle \quad (3)$$

that originates entirely from the interaction with the cell. A polarizer is then placed in the beam's path, which is oriented in the horizontal direction. This constitutes a postselection, only allowing a portion of the beam to continue.

The probability P_{ps} that a photon emerges is simply

$$P_{ps} = \sin^2(\mp\Delta + \phi), \quad (4)$$

which leaves the renormalized postmeasurement state as

$$|\Psi'\rangle = \frac{\sin(\mp\Delta + \phi)}{|\sin(\mp\Delta + \phi)|}|H\rangle|k\rangle. \quad (5)$$

Since $\sin(-\theta) = -\sin(\theta)$, the renormalized state can have only coefficients with a value of ± 1. If the phase shift ϕ can be comparable to Δ, then one can accomplish exactly a π cross-phase modulation in the postselected state. In practice, the polarizers are almost crossed ($\Delta \approx 0$), so the presence (or absence) of the phase ϕ will flip the overall phase of the wave function from 0 to π. This phase shift is then detected by interfering the beam with the other arm of a Mach-Zehnder interferometer (polarization shifted with a wave plate) at a 50/50 beam splitter. The π cross-phase modulation corresponds to a sign change in the postselected beam's wave function, so the photocurrents

$$I_{a,b} = I_0|\psi_l \pm \psi_u|^2 \quad (6)$$

will undergo a change from completely destructive to constructive interference, where ψ_l and ψ_u represent the states of the upper and lower arms, respectively, of the interferometer just before the output beam splitter. The intensity I_0 in Eq. (6) is reduced by a factor of P_{ps} from the original intensity. Although the postselected beam is greatly reduced in intensity, it may still contain a macroscopic number of photons.

In the present experiment, the signal beam [approximately a 2 mm beam waist full width at half maximum (FWHM) and approximately 100 μW] is a diode laser tuned to the red side of the $F = 4 \to F' = 3, 4$ transition of the D_1 line of cesium at 895 nm. In the upper arm of the interferometer, the signal passes through a magnetically shielded 10 cm long Cs vapor cell containing 5 torr of neon buffer gas and heated to approximately 70 °C. In this arm a 30 cm focal length lens focuses the beams into the center of the cell, and another 30 cm lens recollimates the beams. A solenoid is used inside the magnetic shielding to set the magnetic field along the optical axis. When the magnetic field is nearly zero, a coherent population trapping (CPT) resonance (approximately 2 kHz in linewidth) is set up by the two orthogonal circular polarizations ($|+\rangle$ and $|-\rangle$) of the nearly vertically polarized input light. The resulting nonlinear magneto-optical Faraday rotation [20,21] is characterized by moving the atomic system through the CPT resonance by adjusting the magnetic field. After exiting the vapor cell, the signal beam passes through a horizontal polarizer and is then recombined with the free-space path of the interferometer on a beam splitter. The polarization of the signal in the free-space path is rotated using a half-wave plate so as to be horizontal before the output beam splitter, allowing the beams in the two paths to interfere.

The relative path length of the two arms of the interferometer is swept sinusoidally using a piezoactuated mirror, and a balanced photoreceiver is used to obtain the difference signal of the two output ports. The phase of the resulting sinusoidal signal is then monitored on an oscilloscope. Changes in the phase may be introduced by perturbing the CPT resonance either with the magnetic field (for characterization of the system) or all-optically with a separate laser beam external to the interferometer (the "control" beam). When the polarization of the control beam is in the $|+\rangle$ or $|-\rangle$ state, those Zeeman sublevels with dipole-allowed transitions $\Delta F = 1$ or $\Delta F = -1$, respectively, are preferentially shifted. This results in a small difference in the optical path lengths for the $|+\rangle$ and $|-\rangle$ components of the signal beam, giving rise to a small polarization rotation $\pm\phi$.

Before proceeding to the primary experimental results, we first provide some notes about the characterization of the optical resonances involved. Figure 2(a) shows the measured intensities of the signal beam with and without postselection as a function of laser frequency after the cell, in the absence of the control beam. The signal without postselection is shown for reference, indicating the spectral region of experimental operation. The part of the spectrum most sensitive to changes in the magnetic field has been circled, and the inset shows this resonance for various levels of the magnetic field. All of the experimental results reported in this work were obtained by setting the signal frequency near the center of this resonance, though it should be noted that other spectral regions could also have been used. Figure 2(b) shows both the intensity of the control beam as well as the horizontal (postselected) component of the signal beam as a function of the control beam frequency (with no applied magnetic field). Several resonances are visible in the vicinity of the $F = 3$ ground-state Doppler valley. The largest of the peaks (lowest frequency) was found experimentally to have the greatest amplitude dependence on the input polarization of the control beam and was used in obtaining all experimental data reported below. We note, however, that, even when the control field is detuned far from resonance, there are observable changes in the signal amplitude passing through the postselecting horizontal polarizer, indicating that a nondemolition type of phase shift may be possible in this system.

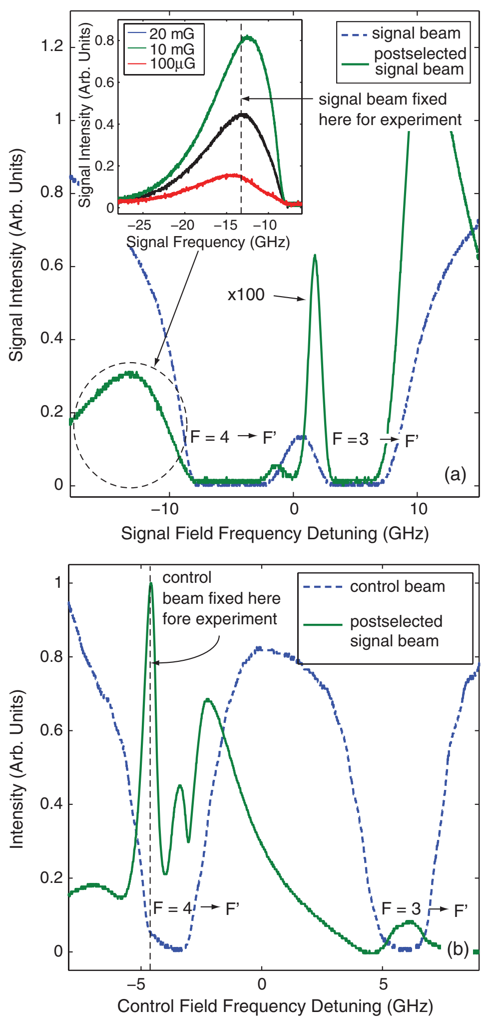

FIG. 2 (color online). (a) Signal beam (895 nm) intensity with (solid green line) and without (dashed blue line) postselection versus signal frequency in the presence of a nonzero longitudinal magnetic field. The spectral region with the strongest dependence on magnetic field strength is plotted in the inset for three different values of magnetic field strength. (b) Postselected signal (895 nm) intensity (solid green line) and control field (no postselection) intensity (852 nm, blue dashed line) versus control field frequency. Zero detuning is defined as the midpoint between the two hyperfine resonances. Power changes are entirely due to atomic absorption for the nonpostselected control and signal beams (blue dashed line) and are normalized to unity transmission.

To characterize the all-optical cross-phase modulation, the magnetic field is set to zero and a 2 mm FWHM control beam, set to be nearly resonant with the D_2 line of cesium at 852 nm, is passed through the vapor cell. The polarization of the control beam is then varied using a quarter-wave plate, and the resulting phase of the electronic signal is monitored. Figure 3 shows the resulting signal recorded by the balanced detector at several control beam powers. The data points are measured values, and the solid line is a sinusoidal fit. It can be seen that the resulting phase of the signal beam is either unchanged (zero) or completely out of phase (π) with respect to the input beam. Figure 3(a) shows the resulting step function with the singularity in phase as predicted by Eq. (5). It is noteworthy that, even though the phase shift imparted to the signal beam is much less than π in the cell, the horizontally polarized projection of the signal beam has a phase change of π to very high accuracy (less than the experimental error of the measurement of about $\pi/100$). Thus, one may achieve a near perfect phase π cross-phase modulation insensitive to control beam power at the cost of reducing power.

The principal experimental results of this Letter were obtained by first setting Δ to zero (perfect cross-polarization) and applying a weak magnetic field to introduce a small polarization rotation ϕ. That shift is then reversed with the control beam, which induces a rotation of approximately -2ϕ, thereby crossing the phase singularity at $\phi = 0$. The resulting phase jump in the postselected signal beam is shown in Fig. 4. The sinusoidal curves are fits to the data and show a phase jump of approximately π (the uncertainty in this measurement was slightly higher than that shown in Fig. 3). While the relative path lengths of the two arms of the interferometer are swept, the control beam is turned on and then off again, resulting in a steep phase jump in the signal at the balanced detector.

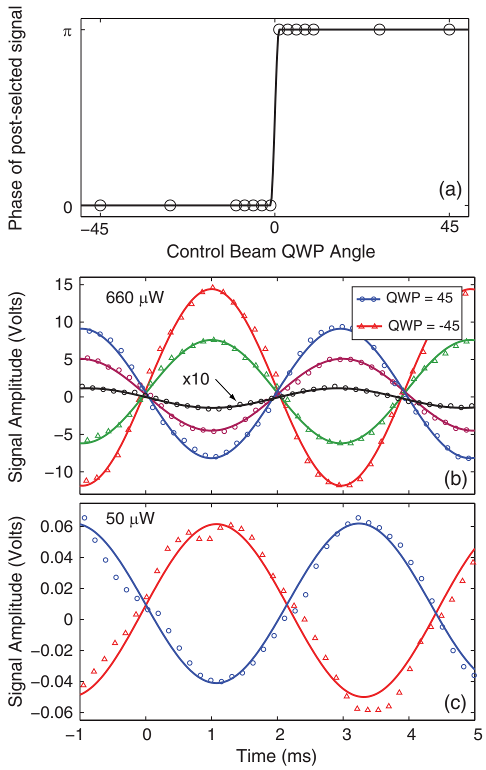

FIG. 3 (color online). (a) Phase of the postselected signal beam versus angle of the quarter-wave plate setting the control beam polarization. The error in the measurement is less than the size of the data points (this plot is valid for all measurable control fields). (b),(c) Signal from the balanced photoreceiver as a function of time as the relative length of the interferometer arms is swept for control powers of 660 and 50 μW, respectively. Each panel represents a different fixed control beam power, and each curve within a panel represents a different polarization of the control beam. Independent of control beam power, as the control beam is changed from right-handed ($|+\rangle$, blue circles) to left-handed ($|-\rangle$, red triangles) circular polarization, the relative phase of the signal beam undergoes a π phase shift, as shown in (a). Other curves in (b) correspond to intermediate values of the quarter-wave plate (QWP) between −45 and 45 degrees.

In summary, we have proposed and demonstrated a mechanism whereby an optical control field may impart a π cross-phase modulation to a separate signal field independent of the optical power of the control field. In the experiment, the interaction between control and signal fields is mediated by a warm vapor of atomic Cs, coherently prepared in a dark state by the signal field. The control field perturbs the dark state, inducing a slight polarization rotation in the signal field. When a polarizer is used to postselect polarization states of the signal field nearly orthogonal to the input signal polarization, the phase of the output signal field is found to be either zero or π radians out of phase with the input signal. This leads to the noteworthy result that π phase jumps may be observed in postselected states of a signal beam even when the relative

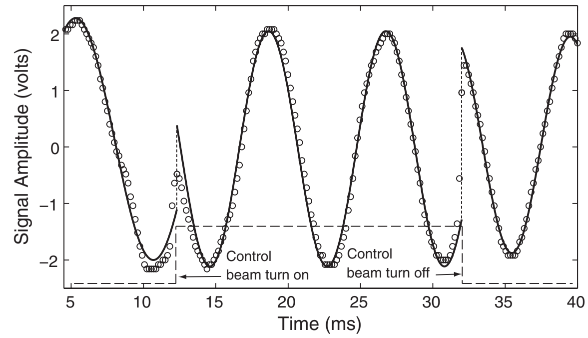

FIG. 4. π phase jump in a signal beam conditional on the presence of a control beam. The control beam induces a small polarization rotation in the signal beam, sufficient to cross the phase singularity shown in Eq. (5).

phase imparted to the entire signal is much less than π. This allows for the amplification of very weak interactions, albeit with attenuation of the measured signal. One hope is that these techniques can aid in achieving a single photon π cross-phase modulation of a macroscopic beam.

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