Far-off resonance conditional phase-shifter using the ac Stark shift

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We suggest a conditional phase-shifter that achieves a phase shift of \( \pi \) radians between two weak laser beams with a total energy density on the level of 1000 photons per atomic cross-section. The two laser beams interact through the simple nonlinear technique of ac Stark shifting the common ground state of a V-type system. We find that this switch can operate in the far-off resonance regime, with low absorption and high phase accumulation. Additionally, the bandwidth of this switch can be increased independently of the energy requirement.

Interacting low-power laser beams is a subject of considerable attention in nonlinear and quantum optics [1–3]. Nonlinear interactions between weak beams can form optical switches with possible applications in all-optical information processing. Furthermore, if achieved at the single photon level, these interactions can also be used to entangle single photons, which may form the basis of a future photonic quantum computing device. In traditional nonlinear materials, the weakness of optical nonlinearities prohibit observing significant nonlinear effects between weak beams. Over the last decade, suggestions involving Electromagnetically Induced Transparency (EIT) have generated much enthusiasm in this field [4–11]. Recent experiments have demonstrated optical switching at \( \approx 10 \) photons per atomic cross-section using EIT-based approaches [10,12]. Additionally, switching with optical instabilities has been demonstrated in an atomic vapor at less than one photon per atomic cross-section [13].

A well-known scheme for interacting laser beams is through the ac Stark shift of a common ground state [1–3]. Here, an intense laser beam can modify the refractive index experienced by a weak beam by changing its frequency detuning from a resonance. In this communication, we analyze this effect in an alkali atomic vapor where the two beams are far-off resonance from the excited electronic state. We find that a conditional phase shift on the order of radians can be obtained with an energy density around 1000 pho-

tons per atomic cross-section, \( \omega^2/(2\pi) \). Our results show that the scheme detailed here could operate as a simple, high-bandwidth, all optical switch with low absorption. Although the physics of what we are going to discuss is well-understood, to our knowledge, the possibility of constructing an ultra-low energy switch by using far-off resonance ac Stark shift has not been discussed before.

Before describing the scheme in detail, we note the several advantages of this approach when compared with similar optical switches utilizing other approaches: (1) This scheme does not require a strong coupling laser as is required by EIT. As a result, the total energy density requirement of our switch is at the 1000-photon level per atomic cross-section. (2) The bandwidth of our switch can be large and one can work with nanosecond time scale optical pulses. The bandwidth can be increased until the rotating-wave approximation breaks down at the expense of an increased density-length product. (3) For sufficiently large detuned beams, Doppler broadening becomes unimportant and as a result, our scheme is well suited for vapor cells. Due to these advantages, our approach may be particularly useful for constructing ultra-low energy, high-bandwidth all-optical switches with possible applications in current fiber-optic networks.

As shown in Fig. 1, we begin with a neutral alkali atomic medium containing a ground state \( |1\rangle \) and two excited states, \( |2\rangle \) and \( |3\rangle \). A probe beam, \( E_p \), and a switch beam, \( E_s \), are tuned far-off resonance from the \( |1\rangle \rightarrow |2\rangle \) and \( |1\rangle \rightarrow |3\rangle \) transitions, respectively. Without the switch beam, the weak probe laser will experience phase accumulation and absorption as determined by the linear susceptibility of the atomic medium. These quantities depend on the probe’s frequency detuning from the atomic resonance, \( \Delta \nu \).

When both the probe and switch propagate together through the medium, the detuning of the probe effectively changes. This is because the switch beam will ac Stark shift the common ground state

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The passage describes a nonlinear phase shift on a probe beam in a V-type atomic medium. The phase shift is due to detunings in the probe beam, which accumulate phase based on the linear susceptibility of the atoms. The plot indicates that ~1000 switch photons per atomic cross-section are required for a phase shift of π radians on the probe.

The equation of motion for the three-by-three density matrix ρ [1]
\[
\dot{\rho} = -i/\hbar [\chi, \rho] - 1/2 (\Gamma, \rho).
\]

The values of ρ_{ij} calculated in Eq. (4) are used to numerically integrate the slowly varying envelope Maxwell’s equations governing the propagation of the probe and switch fields,
\[
\frac{\partial \rho(z, t')}{\partial z} = -i/\hbar \gamma_{ij} N \mu_{12}^2 \rho_{ij}(z, t')
\]
\[
\frac{\partial \rho(z, t')}{\partial z} = -i/\hbar \gamma_{ij} N \mu_{12}^2 \rho_{ij}(z, t'),
\]
where \( \gamma = \sqrt{\hbar/\epsilon_0} \) is the impedance of free space. We solve Eqs. (4) and (5) with the initial condition that all atoms are in ground state [1]. At the start of the atomic medium (\( z = 0 \)) we apply a boundary condition that the fields, and therefore the Rabi frequencies \( \Omega_p(z = 0, t') \) and \( \Omega_s(z = 0, t') \), are long Gaussian envelopes with a Gaussian width of \( \tau \). Eqs. (4) and (5) are then solved on the space-time grid using the method of lines.

The results are presented in Fig. 2 and demonstrate a phase shift of 3.2 radians with 60% transmission. In this simulation, we use the same parameters as the plot in Fig. 1 and use

![Diagram](image-url)
ns \approx 1000 \text{ photons in the switch beam. We observe smooth time-profiles at the end of the medium demonstrating negligible reshaping. Since the probe and the switch beam have identical detunings from the excited state, the switch pulse (not plotted) experiences near-identical absorption and reshaping. Furthermore, the two beams propagate with the same group velocity and therefore stay spatially and temporally well-matched while propagating through the medium.}

Finally, we note that the energy, or number of switch photons, required for this phase-shifter is independent of bandwidth. 

Fig. 3 shows the required detuning and the density-length product for a given bandwidth that achieves the same performance as the numerical simulation of Fig. 2 (a CPS of \sim \pi \text{ radians for } n_s = 1000 \text{ switch photons). As the bandwidth broadens, both the probe and the switch must be appropriately detuned to avoid near-resonance effects. As noted in Eq. (2), if the increased switch detuning is accompanied by a shortened pulse duration, then the switch pulse is more intense for the same energy. The increased probe detuning trades off with an increased OD to keep the probe transmission constant. }

We find that a proof-of-principle experiment showing the fast nature of this phase-shifter is within reach. A vapor cell experiment with \( N = 3 \times 10^{13} \text{ cm}^{-3} \) and a 30 \( \mu \text{m} \) beam waist would require a switch energy of around a picojoule (\( 3 \times 10^7 \text{ photons) to operate at a } \)50 MHz switching rate. These parameters achieve OD = 13,000, as quoted above, in 5 mm of optical length. Alternatively, an experiment in a hollow-core photonic band-gap fiber would be ideal. Exciting advances with this technology have lead to optical depths in excess of 1000 [14]. An optical depth of this magnitude confined to a 6 \( \mu \text{m} \) core diameter could result in a fast conditional phase-shifter to run on the \( 3 \times 10^6 \text{ photon level.}

In summary, we suggested a far-off resonance scheme that supplies a conditional phase shift of \( \pi \text{ with an energy density of } \)1000 photons per \( \lambda^2/(2\pi) \). To the best of our knowledge, the phase-shifter presented here is among the simplest of those suggested in the literature. As mentioned before, a possible application of our suggestion is to all-optical information processing. Among our future investigations is whether our approach may achieve switching at the single photon level, possibly with a high-finesse cavity. If the switch beam can be supplied by a single photon, then the suggestion described here may be applicable as a single-photon controlled-NOT gate between the probe and the switch. This will be among our future investigations.

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References