Fast, all-optical logic gates and transistor functionalities using a room-temperature atomic controlled Kerr gate

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We demonstrate all-optical multilogic gate operations and transistor functionalities using a Kerr phase gate method in a room-temperature 85Rb vapor. Two symmetric Mach-Zehnder interferometers are constructed in the same vapor cell in which a Raman gain medium is established. We show three basic logic gates (AND, OR, and NOT) by controlling the output combinations from the two interferometers. With one weakly driven interferometer acting as the phase control light for a strongly driven interferometer, we further demonstrate optical field-effect transistor functionalities. More complex combinations of this Kerr phase gate method and scheme allow all eight basic logic gate operations including the controlled-NOT gate to be constructed and implemented.

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Logic gates describe a class of logical operations that are the central building blocks of any computers and technologies based on computers, and they form the bases of modern electronics technologies that have deeply permeated into almost every aspect of modern society in an electronic age. As society is moving from the electronic age to the optical age, the development of optical logic gates and optical transistors and the technology based on them naturally presents itself as the next logical step in the pursuit of a technology revolution. Clearly, future optical telecommunications require fast, all-optical logical technologies for a wide range of signal processing applications such as signal regeneration, address recognition, add-drop multiplexing, and all-optical switchings. Optical logic gates constructed from interconnected optical transistors are no doubt the fundamental elements required for the optronics age.

The first all-optical transistor (logic) operation was observed in the context of optical bistability [1], and it consisted of a strong differential gain regime in which small variations in the input intensity can lead to a substantial intensity variation in the output. In the past two decades all-optical transistor operations have been vigorously pursued in photonic band-gap materials [2] and photonics waveguide structures. For instance, a light-emitting field-effect transistor has been demonstrated using a tetracene thin film [3], and transistor operations have been observed in waveguide structures [4]. Furthermore, many studies have been reported using solid-state media and optical fibers to build optical transistors and multilogic gates. These all-optical reconfigurable logic functions mainly utilized nonlinear effects in highly nonlinear materials such as optical fibers [5–7] and a semiconductor optical amplifier [8–10] with a special set of requirements [9–11].

An optical transistor is (mainly) a switching device that operates with photons rather than charged particles such as electrons or holes. It is often heralded as the next logical step in modern all-optical information processing technology, which promises to bring a revolutionary change to society. Precisely because of its potential impact to modern society the idea of an optical transistor and the optical logic gates and circuits based on them have been vigorously pursued. In analogs to an electronic transistor Miller [12] has put forth a set of stringent conditions to characterize the essential functionalities and properties of an optical transistor. These stringent operation criteria include cascatibility, fan out (amplification), logic-level restoration, input-output isolation, absence of critical biasing, and logic level independent of loss. To date, no room-temperature all-optical devices have been able to meet all these requirements simultaneously, especially with very weak gate control light powers.

A large nonlinear phase shift arising from the nonlinear Kerr effect is one of the widely studied nonlinear effects in optical physics. In atomic media both active Raman gain [13] and electromagnetically induced transparency (EIT) schemes [14] can lead to significant nonlinear phase shift effects in the classical field limit. Experimentally, Kerr nonlinear effects arising in EIT media in an N scheme [15] and in an atomic-coherence storage scheme [16] have been studied for potential phase shifting operation, at least in the classical field limit. Recently a fast, all-optical continuously controllable Kerr nonlinear phase gate was demonstrated [17]. In addition, fast digital signal processing based on this controllable Kerr gate operation and high-fidelity fast polarization gate operations have also been demonstrated with record low gate control and switching light powers [18]. The advance of such fast high-fidelity controlled-NOT–polarization gate operations naturally raises the question and interest on whether fast optical logic gates and perhaps even optical transistor-resembling operations can be achieved.

In this paper, we present experimental results of all-optical multilogic gate operations and optical field-effect transistor functionalities using combined and cross-controlled Mach-Zehnder interferometers. We first demonstrate all-optical logic AND, OR, and NOT gates using two symmetrically constructed interferometers. We then demonstrate the functionalities and properties of a field-effect transistor which can meet the requirement of input-output separation and the cascadability. The experimental results presented here represent an atomic-medium prototype device that can largely satisfy all six criteria...
We note that rapid progress in the fields of nanopatterning and nanolithography, in conjunction with advances in materials science, may lead to micro- or nanosystems that integrate the schemes reported for future all-optical communication systems.

Our experiments are performed in a very weak coherent classical field regime. Briefly, we use $^{85}$Rb vapor to demonstrate optical transistor and multilogic gates operations. The atomic vapor is actively temperature stabilized at 335 K (density $10^{12}$ cm$^{-3}$) in the experiment process and the vapor cell is housed in a three-layer magnetic-field shielding chamber (Fig. 1). We first optically pump atoms into the ground state ($|5S_{1/2}, F = 2\rangle$) using a linearly polarized pump laser (wavelength 795 nm, coupling $|5S_{1/2}, F = 3\rangle \leftrightarrow |5P_{1/2}, F = 2\rangle$ transitions). At the end of the optical pumping process a strong horizontal-polarized pump laser (10 mW with a 5-mm beam diameter, wavelength 780 nm) is turned on and drives the $|5S_{1/2}, F = 2\rangle \leftrightarrow |5P_{3/2}, F = 2, 3\rangle$ transitions with a large one-photon detuning of $\delta/2\pi = 1.3$ GHz. At the same time a weak vertical-polarized signal light (50 $\mu$W with a 1-mm beam diameter, wavelength 780 nm) couples $|5S_{1/2}, F = 3\rangle \leftrightarrow |5P_{3/2}, F = 2, 3\rangle$ transitions with the same one-photon detuning $\delta$. The signal field frequency is chosen so that a two-photon Raman transition is established with a two-photon detuning of $\delta_{2\text{ph}} = 700$ kHz. A horizontally polarized phase control light (wavelength 780 nm, 14 mW with a 3-mm beam diameter) couples $|5S_{1/2}, F = 3\rangle$ and $|5P_{3/2}, F = 4\rangle$ transitions with a blue one-photon detuning of $\delta_{\text{ph}} = 400$ MHz.

We demonstrate multilogics using two symmetric interferometers shown in Fig. 1. To cancel the output noise of logic gates, a single temperature controlled cell houses both interferometers to ensure the same temperature effects and density of the medium. In each interferometer the signal light is divided into two parallel parts after being reflected by two surfaces of a 1-cm-thick glass plate. One serves as the reference and another is the signal light upon which the logic gate operation is performed. In both Mach-Zehnder interferometers the reference is controlled by a Piezo-actuator-controlled mirror (PZT). In one interferometer the signal and pump light beams are overlapped anticolonically with a phase control light ($E_{\text{ph}}$). The outputs ($x_1$, $x_2$) of the two Mach-Zehnder interferometers are combined together to form the logic gate output (detectors $D_1$, $D_2$, or $D_3$). In addition, detectors $D_1$ and $D_2$ give the two signal inputs [$E_{\text{S1}}$ and $E_{\text{S2}}$, respectively, controlled by their own acousto-optic modulators (AOMs)]. For simplicity, the phase control field $E_{\text{ph}}$ is derived from the $-1$st-order output of the second signal laser and is further amplified. The two interferometer outputs are normally either both “0” for an AND gate or both “1” for an OR gate depending on the choice of PZT voltage. A separate clock signal is used for timing of the input-output sequence.

In Fig. 2(a) we show the AND and OR gates operations with two independent input signal lights. For the AND gate we normally take $x_1 = 0$ and $x_2 = 0$ while for the OR gate operation we normally set $x_1 = 1$ and $x_2 = 1$. The digital waveforms are encoded randomly into the two input signal lights whereas the phase control light pulse is controlled...
separately. In the experiment, a $\pi$ phase shift is induced in the input signal light in the first interferometer when the second input signal light is turned on. For the OR gate, the output of the first interferometer is flipped from “1” to “0” when the second input signal light is at the “1” state while the output of the second interferometer is maintained as “1.” The detector $D_1$ outputs “1” when either one of two input signal lights is “1” and outputs “0” when both input signal lights are “0,” as required for an OR gate operation [the second trace from the bottom in Fig. 2(a)]. For the AND gate, the output of the first interferometer is flipped from “0” to “1” when the second input signal light is on (state of “1”) while the output of the second interferometer is maintained as “0.” The detector $D_1$ outputs “1” only when the two input signal lights are both “1,” otherwise it outputs “0” as required for an AND gate operation [the bottom trace in Fig. 2(a)].

The NOT gate operation is shown in Fig. 2(b). Here, the outputs of the first and second interferometers are normally $x_1 = 1$ and $x_2 = 0$, respectively. The combined output is detected with detector $D_2$. The first input signal light is a clock pulse train (bias) whereas the second input signal light is encoded with randomly distributed “0” and “1” signals. Therefore the first interferometer can be control flipped using the phase control light by introducing a $\pi$ phase shift. When a $\pi$ nonlinear phase shift is introduced to the first interferometer its output flips from “1” to “0.” If the second input signal light outputs a “1” (“0”) the combined output becomes “0” (“1”), as required by a NOT gate operation.

The principle demonstrated in this work can also be used to demonstrate some of the most basic properties of an all-optical transistor. Indeed, the multilogic gates operations described above and the fundamental principles of the scheme indicated that the requirements of cascadability, fan-out capability, and the absence of critical basing proposed by Miller [12] can be largely fulfilled. Furthermore, the requirements of logic level restoration, input-output isolation, and logic level independent of loss can also be partially achieved. In fact, with some modifications we are able to demonstrate all eight logic gate operations including a controlled-NOT (CNOT) operation, upon which all known electronic circuits are based. Typical operation of an electronic transistor requires that a weak and noisy input signal light at the base be amplified and requires a noise-free output at the emitter while the collector is positively biased (depending on the type of transistor) and constantly biased. This functionality can be mimicked using one weakly driven input light controlling the output of another strongly driven interferometer. Here, the weak input light is used as the phase control light for the high intensity output of the interferometer. The pulsed transistor output is decided by the interferometer normally output ($x = “1”$ or “0”) at one exit port. In Fig. 3 we show the normally “on” and normally “off” field-effect transistor characteristics for a pulse train with different input light intensities. The interferometer output is normally “1” for a normally “on” transistor state while it is normally “0” for the normally “off” transistor state by the choice of fixing PZT voltages and the actual nonlinear phase induced by the phase control light. The strong light is always turned on and the output intensity depends on the weak input light intensity. The output light intensity is decreased for the normally “on” transistor state while it is increased for the normally “off” transistor state as input light intensity is increased. The output is zero for a completely closed normally “on” transistor state while it is maximum for a completely open normally “off” transistor state where a $\pi$ nonlinear phase shift is added to the arm. This result indicates the input-output isolation, which is an important criterion proposed by [12].

FIG. 3. (Color online) Demonstration of all-optical field-effect transistor functionalities using a $\pi$ phase shift Kerr gate. The normally “on” (red, middle trace) and “off” (blue, bottom trace) emitter of field-effect transistor functionalities are controlled by the output of the lower interferometer at its normal “1” and “0” ports. The base input field ($E_{32}$) (black, top trace) is optically amplified and then injected into the lower Mach-Zehnder interferometer to control and induce a $\pi$ phase shift to the collector input field ($E_{31}$). Constant collector intensity is not shown.

FIG. 4. (Color online) Demonstration of logic level restoration and logic level noise immune functionalities of an optical transistor. The transistor is normally at an “off” state. A random noise is superimposed to a single logic pulse input field (base input, top trace). The output shows a well restored logic level (emitter output, second trace from top). Multidigital input signal with random noise (base input, third trace from top) and the output multidigital signal (emitter output, bottom trace) showing the noise immune ability of the device.
Logic level restoration of an optical signal is one of the more difficult tasks. Contrary to the electric logic level restoration, where both the signal waveform and timing characteristics must be preserved, the optical counterpart requires, in addition to the signal waveform and timing characteristics restoration, a stringent beam quality restoration. The data presented in Fig. 4 show that the noise and degradation of the signal quality do not propagate through the system. The experimental setup is similar to that demonstrating the field-effect transistor shown in Fig. 3 except that the optical amplifier works in the saturation regime. The phase control light intensity is chosen so that a $\pi$ nonlinear phase shift is maintained for the interferometer signal light ($E_{S1}$) (we imposed a random noise to the second input field $E_{S2}$, see base input traces). Both pulsed and continuous-wave operations are investigated to confirm the transistor properties based on the nonlinear Kerr effect and Mach-Zehnder interferometer using an active Raman gain medium. The emitter outputs clearly demonstrate “cleaned” outputs of the transistor, establishing the capability of logic level restoration and logic level independent of loss.

The scheme described above for optical transistor functionalities is just one of many possible combinations using the $\pi$ phase shift Kerr gate and it has already stimulated new studies in this direction [19]. In principle, it can be shown that all seven basic logic gates and the controlled-NOT gate can be realized with this method. Indeed, integrating four individually controlled and Kerr gate based Mach-Zehnder interferometers in a single cell of gain medium can lead to a variety of operation logics and functionalities. As nanotechnology progresses and the ability of integrating microsize optical elements becomes more robust, devices based on the principle demonstrated in the present work will be realized in integrated optics.

In conclusion, we have demonstrated optical AND, OR, NOT logic gate operations using a $\pi$ phase shift Kerr gate method in an active Raman gain medium. We have also shown several important functionalities of an all-optical transistor, which to a large degree fulfill all six critical criteria for a realistic optical transistor outlined by Miller [12]. The functionalities of a field-effect transistor demonstrated show the capability of the Kerr gate in optoelectronic device applications. We note that with simple modifications the scheme described here can achieve all seven classical logic gate operations in addition to the controlled-NOT gate upon which any computation architecture can be built. It is reasonable to speculate that with nanotechnology and advanced engineering materials the schemes and methodology reported here may lead to optoelectronic devices with much faster operation speed, much more operation complexity, much smaller footprints, and significantly lower energy consumption.

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