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Optical logic gates using coherent feedback

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We experimentally demonstrate optical logic "OR" and "NOR" gates via coherent feedback. Based on a four-wave mixing process in hot rubidium vapor, two feedback beams are capable of fulfilling an optical "NOR" gate for the feedback-suppressed state and an optical "OR" gate for the feedback-boosted state simultaneously. The logic gates exhibit transition times faster than previously demonstrated in rubidium vapor. Coherent photon conversion between the two logic states, due to the atomic coherence, is observed in the coherent feedback process. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4767133]

Optical logic gates are of interest in optical communication schemes and are necessary for optical computation. We utilize the principle of coherent feedback, which has been developed to dynamically control, stabilize, and enhance the performance of optical processes,[1–5] in order to create robust optical logic gates. Compared with feedback based on measurement, coherent feedback has the advantage of instantaneous control, preserving coherent information and avoiding the introduction of excess measurement noise. Here, we demonstrate optical "OR/NOR" gates in a four-wave mixing (FWM) process with coherent feedback in rubidium vapor. In the process, two feedback beams are capable of fulfilling an optical "NOR" gate for the feedback-suppressed state and an optical "OR" gate for the feedback-boosted state. The logic gates exhibit transition times faster than previously demonstrated in rubidium vapor. Coherent oscillatory behavior between the two logic states is observed in the dynamical regime. This indicates the existence of coherent coupling between the two logic states due to atomic coherence.

The FWM process in rubidium vapor provides the mechanism allowing control of the output signal via feedback of the seed beams. Efficient four-wave-mixing processes enhanced by atomic coherence in multilevel atomic rubidium systems have been the subject of many studies.[6–10] Hemmer *et al.* have shown that owing to the atomic coherence, FWM with a gain of 55 can be achieved.[7] Nondegenerate FWM based on the coherent conversion process between the atomic coherence and the FWM signal has also been investigated.[8] Recent experiments have utilized FWM in atomic double-lambda systems to achieve dramatic nonlinear optical phenomena such as four-wave-mixing stopped light,[11] ultraslow matched pulses,[12] superluminal light,[13] and macroscopic squeezed light.[14,15] The optical "OR/NOR" gates demonstrated here rely on FWM based on the double-lambda system in hot rubidium vapor. A schematic diagram shown in Fig. 1(a) outlines the optical logic gates. The scheme provides the advantage to control the strong beams via weak feedback beams, which allows for the possibility of cascadable photonic logic devices.

The optical logic gates make use of two bright spots in output state "V" (Fig. 1(b)), which are generated through a spontaneous double-lambda FWM process (Fig. 1(c)) and then coherently fed back into the cell as the controlled seeding. The seeded FWM leads to two bright spots in state "H" and suppresses the state "V." Inputs a and b are used to encode the feedback beams and generate the input Boolean logic strings. The double-lambda FWM scheme used here involves a strong pump beam blue-detuned by roughly 1.4 GHz relative to the Rb D1 line. Mediated by the $\chi^{(3)}$ nonlinearity, pump photons are annihilated, and Stokes and anti-Stokes photons are created in pairs that propagate at equal angles on opposite sides of the pump.

The optical configuration of our experimental setup for the optical logic gates is depicted in Fig. 2. A linearly

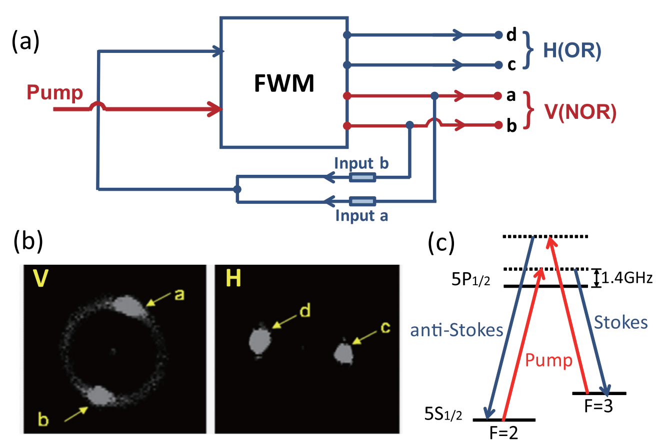

FIG. 1. (a) A schematic diagram of optical logic gates based on FWM. (b) FWM output pattern observed in the far field for the case without feedback (state "V") and with feedback (state "H"). (c) Double-lambda FWM energy level scheme.

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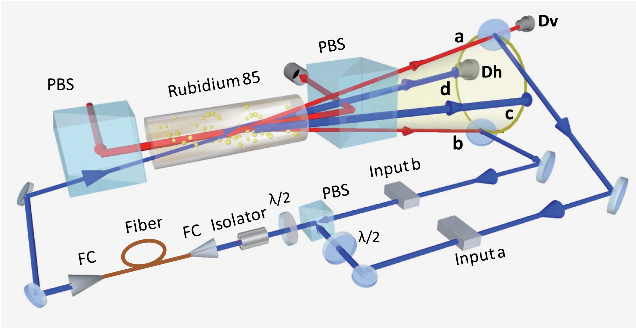

FIG. 2. Schematic of the experimental setup consisting of the cell, the pump and feedback beams, PBSs, half-wave plates ($\lambda/2$), optical isolator, fiber, fiber couplers (FCs), and inputs a and b, which are used for encoding the feedback beams "a" and "b." Dv and Dh are detectors placed in the spots of beams "a" and "d."

polarized beam with a power of 285 mW ($2.28\,\mathrm{watts/cm^2}$) from a Ti:sapphire laser is used as the pump. The cell containing naturally abundant rubidium is 7.5 cm long and held at a temperature of 145 °C, corresponding to an atomic density of 4×10^{13} ^{85}Rb atoms/cm^3. A polarization beam splitter (PBS) after the cell is used for filtering out the residual pump beam. A conical emission in a ring pattern with a half-angle cone of roughly 8 mrad is formed when the pump is blue-detuned 1.4 GHz from the $5S_{1/2}$ (F = 2) to $5P_{1/2}$ transition of ^{85}Rb D1 line. The frequency difference between the pump laser and the conical emission spectral components is approximately ±3.035 GHz (the ground-state hyperfine splitting of ^{85}Rb), with one component red-shifted (Stokes sideband) and the other blue-shifted (anti-Stokes sideband) by this amount. This observation indicates that the mechanism of conical emission is the parametric FWM process,[16,17] which satisfies the phase-matching and energy conservation conditions (Fig. 1(c)). The majority (up to 93%) of the conical emission spectrum is anti-Stokes sideband. This is due to the fact that the absorption of the Stokes sideband is significantly larger than that of the anti-Stokes sideband in the present high atomic density regime. Because the unseeded conical emission is extremely sensitive to any small asymmetrical disturbance in the system,[16,18] the far-field pattern can be altered to two bright spots accompanied with a background ring. This pattern is employed to represent the state "V" of logic gates, as shown in Fig. 1(b). Although other possible patterns in the system are also applicable as the logic states, such a specific one is more convenient for the realistic operation of the gates, such as ease of detection.

The far-field pattern of beams "a" and "b" in Fig. 1(b) are the spontaneous output modes of the unseeded FWM process, whereas that of beams "c" and "d" correspond to the output of the FWM stimulated by feedback beam. We take out a significant amount of light from beams "a" and "b" (up to 98%) as feedback to ensure strong feedback. The feedback beams are then encoded through a pair of control gates "input a" and "input b" to generate input Boolean strings. Each of the "input a" and "input b" consists of two acousto-optic modulators (AOMs) with rise times of approximately 100 ns. The two AOMs induce equal but opposite frequency shifts and can thus be used for amplitude modulation without introducing any frequency change in the beams. We emphasize that except the two AOMs as the input ports, all essential parts in the experiment and the physics behind it completely rely on all-optical operation with light controlling light. In fact, the use of the AOMs is not essential here, and is used only to generate the Boolean signals for a proof-of-principle demonstration. The AOMs can be replaced by an all-optical way to encode the feedback beams. All-optical control of light beams has been well-developed in the areas of photonics and optical communications.[19,20]

After being combined with a PBS, beams "a" and "b" are adjusted by a half-wave plate, and then sent through an optical isolator that only passes horizontally polarized light, thus allowing us to tune the output power. The combined light beam is spatially coupled into a multi-mode fiber, and then input into the vapor cell at a direction that maximally overlaps with the output ring in order to meet the phase-matching condition. The orientation of the combined feedback beam, however, is chosen in the horizontal plane (referred to as "H"), orthogonal to the original two-spots' vertical direction (referred to as "V") (Fig. 1(b)).

The spectrum of the output state "V" of the spontaneous FWM process suggests that the FWM process can effectively be viewed as two Raman scattering processes (see Fig. 1(c)). The first Raman process starts from ground-state hyperfine level $F = 2$ by the pump coupling and ends at hyperfine level $F = 3$ with the spontaneous emission of the Stokes photons. Meanwhile, this process generates the ground-state atomic coherence,[21] a coherent superposition of the two ground-state sublevels $F = 2$ and $F = 3$. The atomic coherence can induce the emission of anti-Stokes photons again through the strong pump coupling in the second Raman process from $F = 3$ to $F = 2$. In the sense, the atomic coherence acts as a mediator which induces the coupling between the photons in the FWM process.[8,11,22,23]

By seeding the feedback beam in the horizontal plane "H," the seeded Stokes and anti-Stokes photons cause stimulated FWM which generates the output state "H." The stimulated FWM takes place rapidly. The input beams are significantly amplified, and the beam spots in the output state "V" of the spontaneous FWM are greatly suppressed since the stimulated FWM competes with the spontaneous one for the same atomic coherence they share. As a result, the output state "V" is switched to the output state "H." This occurs when the feedback beams are "on" in either "input a" or "input b," or both. During the whole process, the background ring remains to provide feedback photons (The background ring is not visible in state "H" shown in Fig. 1(b) due to the fact that the contrast ratio between the bright spots and the ring is large.). When the feedback beams are "off" in both inputs, the state "V" is switched back by the spontaneous FWM. Therefore, controlling beams "a" and "b" can simultaneously fulfill the logic "NOR" gate for "V," and the logic "OR" gate for "H." Experimentally, we find that the "V" state is most easily generated with the feedback beam injected in the plane "H." Due to the phase insensitive nature of this type of process,[24] the logic gates are very robust and last the entire duration of the experiment without requiring any phase stabilizing techniques.

We first investigate this feedback stimulated FWM process by measuring the average power in the state "H" when

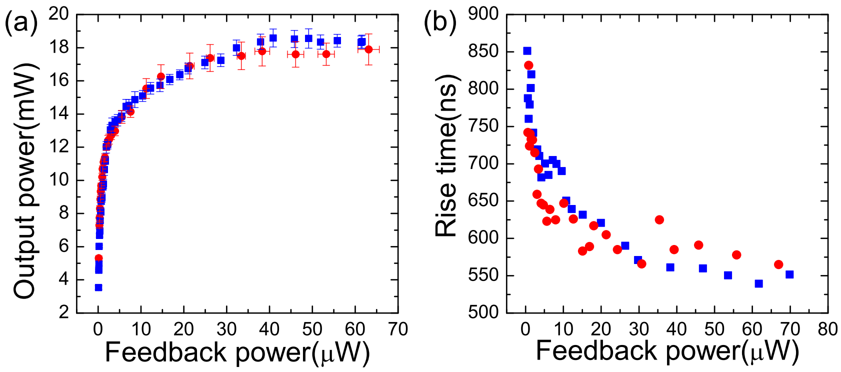

FIG. 3. (a) Output power in the feedback-boosted state versus power of the two feedback beams "a" (red circles) and "b" (blue squares), where the error bars are the standard deviations. All error bars shown in the figures include both statistical and systematic errors. (b) Rise time of beam "d" in the feedback-boosted state versus power of the two feedback beams "a" (red circles) and "b" (blue squares). The rise time signals are averaged 1000 times and the systematic errors are approximately 20 ns.

the FWM is seeded by one of the two feedback beams. The results for feedback with beams "a" and "b" are plotted in Fig. 3(a). In both cases, the output power increases rapidly with feedback before it reaches a saturation output power level of about 18 mW. The figure further reveals the property that a weak beam can efficiently manipulate a strong one. The ratios of the output beams' powers to the injected beams' powers in the saturated regime can be up to 500 for both feedback injected beams. The fact that the FWM output power depends on the seed power, is amplified, and then saturates, is integral to the operation of the logic gates.

As seen in Fig. 3(b), the rise times of signals in the state "H" decrease as the injected powers increase, saturating at around 550 ns, which is roughly two times faster than the best previous result.[16,25] The improvement is due to the fact that the stimulated FWM process, enhanced by the atomic coherence, occurs rapidly. The rise time limit is determined by system parameters such as laser beam sizes, the one-photon detuning, and the velocity of the atoms.

The optical logic gates are demonstrated in Fig. 4. The input signal pulse sequences from inputs a and b of the two feedback beams are with Boolean input values (00110011001) and (10011001100) (noting that "1" represents state "ON" and "0" represents state "OFF"). The half-wave plate before the isolator is set such that both feedback beams transmit equal power.

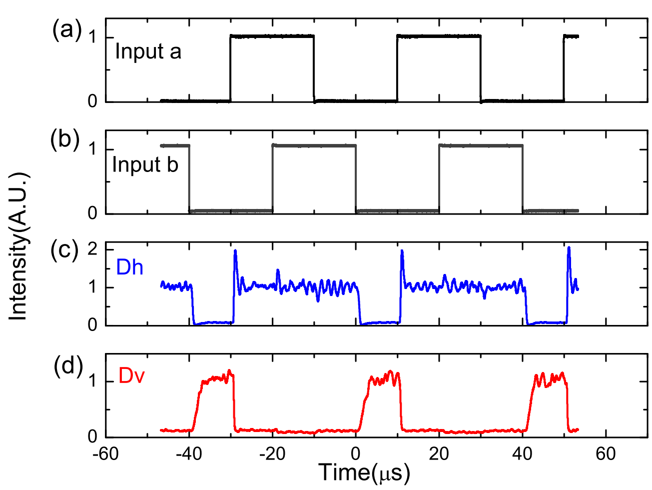

FIG. 4. Behavior of the logic devices. Plots (a) and (b) are the signals from inputs a and b, which encode the two feedback beams "a" and "b," and plots (c) and (d) are the output signals from beam "d" in the feedback-boosted state and beam "a" in the feedback-suppressed state, which are detected by detectors Dh and Dv, respectively.

The corresponding output signals in the operation of the logic gates are detected by detectors "Dv" and "Dh." For the output detected by "Dh" located at the spot "d" of the state "H," the corresponding logic state is (1011101110), equivalent to the logic "OR" gate; while for the output detected by "Dv" located at the spot "a" of the state "V," the logic state is (0100010001), which fulfills the "NOR" gate function. The "OR/NOR" logic gates are both able to switch with an efficiency of more than 93%. The transition times (rise time and fall time) of the "OR" gate and the fall time of the "NOR" gate, all observed around 550 ns, are faster than previously demonstrated in rubidium vapor. This is a direct result of employing the stimulated FWM process for the operation of the gates. We also note that the rise time of the "NOR" gate is slower due to the fact that the state "V," relying on the spontaneous FWM process, takes a longer time to "switch" back. As shown in Fig. 4, the logic gates exhibit a high level of logic consistency, i.e., the output levels of "0" and "1" are highly consistent with the Boolean input values.

It is also worth noting that the output signals in Fig. 4 exhibit oscillatory behaviors when one of the feedback beams is suddenly turned on from their off state. The enlarged oscillations are shown in Fig. 5(a), where the blue (red) curve corresponds to the time evolution of light intensity at the spot "d" ("a"). The oscillatory natures of the light intensities clearly reflect the competition between the stimulated FWM process (generating the state "H") and the spontaneous FWM process (generating the state "V") during the coherent feedback. Since the atomic coherence plays an important role in the competition, the oscillations decay to the steady state due to the atomic decoherence, which is typically in a time scale of a few μs in the present system of rubidium vapor. This coherent oscillation phenomenon was not observed in the case without the coherent feedback and atomic coherence.[16]

The oscillation frequency of the two FWM light intensities is investigated as well. The results are shown in Fig. 5(b), where the oscillation frequency ω versus the square root of the pump power is plotted. The conical emission only becomes measurable when the pump power is above 200 mW, thus the plot starts from around 14 $\sqrt{\text{mW}}$. The solid line is a linear fit to the experimentally measured data. This indicates that the oscillation frequency linearly depends on the pump light field, which couples the output signals and the atomic coherence.

The present results suggest that it would be possible to measure squeezing and quantum correlations between beams used in the optical logic gates, due to the quantum nature of the FWM process.[14,15] Additionally, the present work also

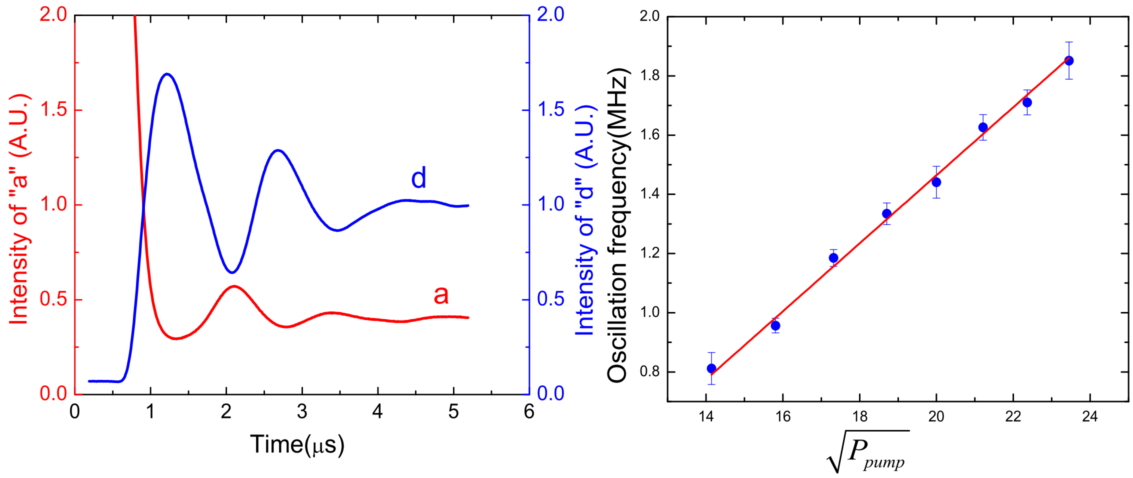

FIG. 5. (a) Observed oscillation between the intensity of beam "a" (red solid) in the feedback-suppressed state and the intensity of beam "d" (blue solid) in the feedback-boosted state. (b) The oscillation frequency ω versus the square root of the pump power.

leaves space for future experiments to use coherent feedback to explore the nonclassical light including the enhancement of quantum squeezing in the FWM process.[5,15] Using intensity-difference squeezed beams generated by the FWM process as the feedback beams would allow for investigations into how the coherent feedback affects the level of squeezing generated. Coherent feedback can also be extended to stabilize the output signal in optical processing based on atomic systems.[3]

In summary, we experimentally demonstrate optical "OR/NOR" gates using coherent feedback via the FWM processes in hot rubidium vapor. The optical gates show a significant improvement in operation speed with transition times faster than previously demonstrated in rubidium vapor. The coherent oscillation between the two output logic states is demonstrated. The nature of the optical logic gates may have potential in the future development of optical communications and optical information.

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