Logic operations in a doped solid driven by stimulated Raman adiabatic passage

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We experimentally demonstrate classical-optical logic operations in a solid-state memory, coherently driven by variants of stimulated Raman adiabatic passage (STIRAP). Cyclic transfer of atomic populations permits the implementation of a flip-flop or XOR gate, with up to eight optical input operations. Observation of stimulated emission as an additional output channel enables the setup of a STIRAP-driven full adder for three optical input bits (or two input bits and a memory bit).

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I. INTRODUCTION

Future implementations of information technology require concepts in the framework of optics, in order to increase capacity and performance of data processing. Recent developments in quantum optics already provide some basic solutions to approach these goals. We note here, e.g., the concepts of quantum memories, qubits, and quantum computations. These concepts typically involve coherent light-matter interactions. However, it will still be a long path from basic quantum computations in simple atomic systems toward future quantum information technology under realistic conditions—most probably implemented in solids. Thus, we require intermediate steps between today's classical, electronic data processing and future, optically driven quantum technology. The following work deals with the application of coherent light-matter interactions (i.e., the basis of any optical quantum technology) to drive classical logic operations (i.e., the basis of today's information technology) in a solid-state quantum system. Our work aims at coherent-optical logic gates and finite state logic machines. Both are the essential components of any computer—no matter whether classical or quantum. While the output of gates depends on the input only, the output of a finite state machine depends both on the input and the present state of the machine (i.e., the memory).

So far classical optical computing has implemented logic functions by manipulating the (macroscopic) beam path and intensity of light [1–3]. These schemes have now reached the time scale of picoseconds [4,5]. However, none of these approaches applies adiabatic interactions of light with matter and none uses microscopic memory. So far there is in no demonstration of an optical adder in a microscopic quantum system at all. We note here some recent optical implementations of quantum gate operations [6–8] and quantum data storage [9,10], which involve the interaction of light with matter, e.g., in rare-earth-doped crystals. Here, the efficient manipulation of quantum states is a crucial requirement. Adiabatic excitations are well-established tools to permit both efficient and robust manipulation of quantum systems. Examples are electromagnetically induced transparency (EIT) [11] and stimulated Raman adiabatic passage (STIRAP) [12]. The latter permits complete and selective population transfer between the ground states of a three-level system in Λ-type configuration. STIRAP has been extensively applied in the gas phase, and recently it was also implemented in a doped solid. [13–15]. The latter combines the advantages of solids (i.e., large density and scalability) and atoms in the gas phase (i.e., narrow linewidths and long decoherence times).

To push coherent-adiabatic interactions toward logic machines, Remacle *et al.* recently proposed a STIRAP-like coupling scheme to drive logic operations [16]. We will briefly review the well-known concept of STIRAP, some extensions, and the recent idea of [16]: Consider a three-level scheme of bare states $|0\rangle$, $|e\rangle$, and $|1\rangle$. The system is initially in state $|0\rangle$. A pump laser pulse couples states $|0\rangle$ and $|e\rangle$. A Stokes laser pulse couples states $|1\rangle$ and $|e\rangle$. The Rabi frequencies are $\Omega_P = \mu_{0e} E_P/\hbar$ and $\Omega_S = \mu_{1e} E_S/\hbar$ with the electric fields E of the lasers and the dipole transition moments μ. We describe the dynamics of the system in terms of adiabatic eigenstates:

$$|b\pm\rangle = (\sin\theta|0\rangle + \cos\theta|1\rangle)\sin\phi \pm \cos\phi|e\rangle, \quad (1)$$

$$|d\rangle = \cos\theta|0\rangle - \sin\theta|1\rangle, \quad (2)$$

with the mixing angles $\theta(t) = \arctan|\Omega_P(t)/\Omega_S(t)|$ and $\phi(t) \approx (1/2)\arctan(\Omega_P^2 + \Omega_S^2)^{1/2}/\Delta$. The adiabatic states $|b\pm\rangle$ include the excited state $|e\rangle$, which is subject to fluorescence decay. Thus, states $|b\pm\rangle$ are *bright states*. The adiabatic state $|d\rangle$ does not contain the excited state $|e\rangle$. Thus, $|d\rangle$ is a *dark state*. A counterintuitive pulse sequence (i.e., Stokes pulse preceding pump pulse, in the following termed an SP pulse pair) permits complete adiabatic population transfer from state $|0\rangle$ to state $|1\rangle$, via the *dark state* $|d\rangle$. This is the essence of STIRAP. An intuitive pulse order (i.e., pump pulse preceding Stokes pulse, in the following termed a PS pulse pair) may lead to efficient adiabatic transfer from state

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$|0\rangle$ to state $|1\rangle$ via the *bright states*. This is possible if the laser frequencies of the PS pulse pair are slightly detuned from resonances. This process is called b-STIRAP [14]. As an important conclusion, a repeated application of SP pairs with slightly detuned frequencies in a three-level scheme results in cyclic transfer between $|0\rangle$ and $|1\rangle$. The first SP pair drives the system from $|0\rangle$ to $|1\rangle$ by STIRAP. The second SP pair drives the system back from $|1\rangle$ to $|0\rangle$ by b-STIRAP—as the exchange of the initial state is identical to the reversal of the pulse order from SP to PS. We can monitor the direction of the transfer, e.g., by fluorescence from the excited state, as only b-STIRAP leads to a (small) transient population of state $|e\rangle$.

Remacle *et al.* theoretically proposed to apply the concept to set up an optical full adder [16]. A full adder has three inputs, termed input a, input b, and carry-in. The full adder calculates the sum of the two inputs and a carry-in (e.g., a memory bit). In our coherently driven system, the inputs a and b may be optically represented by two SP pairs. The logic value of an input is 0, if no SP pair is present. The logic value of an input is 1, if a SP pair is present. The carry-in bit may be represented by a third SP pair or the memory, i.e., the state of the system. The adder has two outputs, usually termed sum and carry-out. The two outputs represent the binary two-bit value of the addition (input a) & (input b) + (carry-in). As outputs, Remacle *et al.* propose to monitor fluorescence from the excited state (which defines the carry-out) and the final state of the system after interaction with the SP pulses (which defines the sum bit). From Table I we see that the dynamics of a three-level quantum system, initially prepared in state $|0\rangle$ and driven by SP pulses, perfectly resembles a full adder. This logic scheme cannot be implemented by alternative coherent interactions, e.g., π pulses. The latter do not permit determination of the transfer direction, which is required for an adder. Moreover, π pulses in effective two-level systems permit only very simple logic functions with one output, while complex logics (e.g., an adder) require more.

TABLE I. Truth table of a full adder. The bottom line indicates the physical properties in a coherently driven three-level system, which represent the logic inputs and outputs. Consider, e.g., the addition of input a = 1, input b = 1, and carry-in = 0 (see fourth line in the table). In this case, the quantum system is initially in state $|0\rangle$ and interacts with two SP pulses. The SP pulses drive the system from $|0\rangle$ to $|1\rangle$ by STIRAP and back to $|0\rangle$ by b-STIRAP. Thus, the final state is $|0\rangle$, defining sum = 0. As b-STIRAP is involved in the process, we observe fluorescence, which defines carry-out = 1. Thus, the binary sum of 1 + 1 + 0 yields (10).

Input a	Input b	Carry-in	Carry-out	Sum
0	0	0	0	0
0	1	0	0	1
1	0	0	0	1
1	1	0	1	0
0	0	1	0	1
0	1	1	1	0
1	0	1	1	0
1	1	1	1	1
SP pair 1	SP pair 2	initial state	fluorescence	final state

We slightly modify the above scheme to set up optical logic operations in a doped solid. We use stimulated emission (i.e., amplification of a probe laser) rather than fluorescence to define the carry-out bit. Moreover, we use the detuning as a control parameter in b-STIRAP, in order to optimize specific logic operations. In the following, we will discuss the experimental implementation of an optical XOR gate (which may also be understood as a flip-flop) and an optical full adder in a solid memory, i.e., a rare-earth-ion-doped Pr^{3+}:Y_2SiO_5 crystal.

II. EXPERIMENT

Figure 1 shows the relevant coupling scheme in Pr^{3+}:Y_2SiO_5. For details with regard to the doped crystal, cryogenic cooling, and optical preparation we refer the reader to [15]. By spectral hole burning we prepare the system in Λ-type configuration. In addition to the SP pairs, a probe laser pulse serves to determine the state of the system, i.e., occurrence of absorption by population in state $|1\rangle$. The laser pulses are deduced from a frequency-stabilized ring dye laser, providing cw radiation at 606 nm. The laser radiation is split into three beams, which are modulated in frequency and amplitude by acousto-optical modulators to generate pump, Stokes, and a weak probe pulse. The duration of the laser pulses is 20 μs (FWHM). The peak Rabi frequencies driven by the SP pulses are 1 MHz.

Figure 2 shows absorption spectra, when the probe laser is tuned in the vicinity of the Stokes transition between $|1\rangle$ and $|e\rangle$. Figure 2(a) depicts the spectrum 500 μs after the preparation sequence, without application of an SP pair. The system is initially in state $|0\rangle$ and stays there. As state $|1\rangle$ is empty, no absorption occurs. Figure 2(b) shows the spectrum 200 μs after the first SP pulse pair. The system is driven by STIRAP to state $|1\rangle$. Thus, the probe laser detects strong absorption. Figure 2(c) shows the spectrum after application of a second SP pair, which transfers population back from $|1\rangle$ to $|0\rangle$ by b-STIRAP. Thus, the absorption maximum is now strongly reduced. We note that the absorption is not

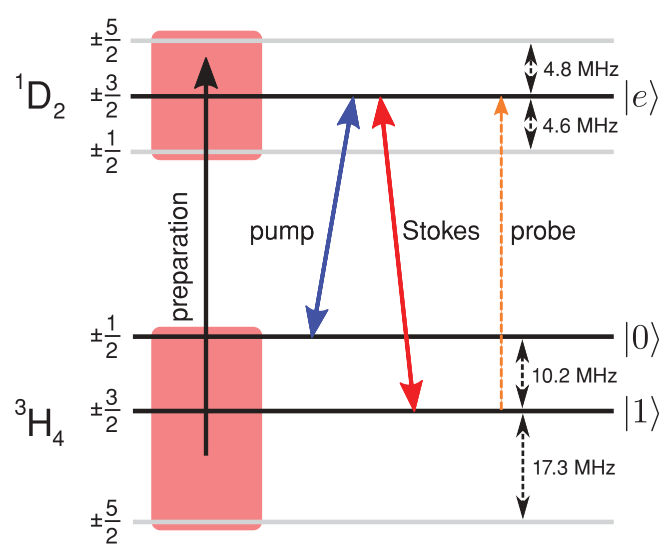

FIG. 1. (Color online) Coupling scheme in Pr^{3+}:Y_2SiO_5.

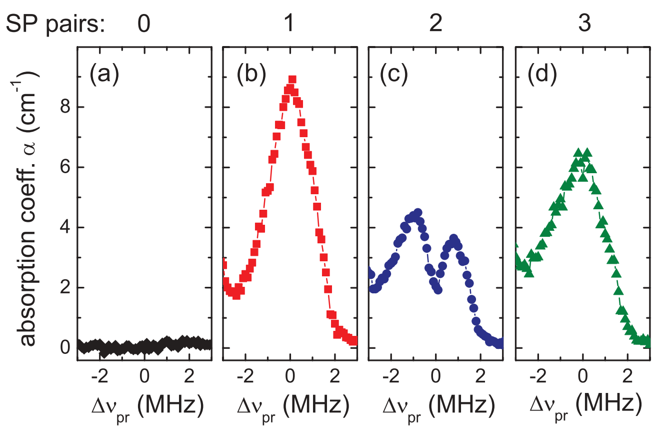

FIG. 2. (Color online) Absorption spectra after excitation with SP pulse pairs. The probe frequency $\nu_{\rm pr}$ is defined with respect to the transition between $|1\rangle$ and $|e\rangle$. (a) Spectrum after preparation by optical pumping, without application of SP pulses. (b) Absorption spectrum after a first SP pair. (c) Spectrum after a second SP pair. (d) Spectrum after a third SP pair.

reduced completely to zero because incoherent losses during the transfer process leave some residual population in $|1\rangle$. Figure 2(d) shows the spectrum after a third SP pair, which drives the system again from state $|0\rangle$ to state $|1\rangle$. Absorption (i.e., population in state $|1\rangle$) increases toward the value after the first SP pair.

To implement a simple logic gate, we monitor the absorption dynamics for a sequence of eight SP pulse pairs. Figure 3 shows the absorption changes at a relative probe frequency of $\Delta\nu_{\rm pr} = -0.7$ MHz. Labels in the figure indicate the number of applied SP pulses.

The measurement shows a fast switching of the absorption, each time an SP pair interacts with the system. After an odd number of SP pairs, we observe high absorption (as the system or memory is finally driven to state $|1\rangle$). For an even number of

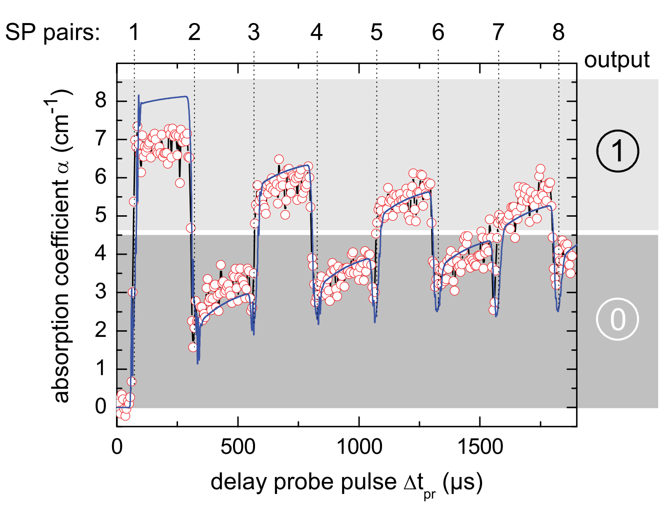

FIG. 3. (Color online) Absorption dynamics for cyclic population transfer by up to eight SP pairs. Red, open circles represent experimental data. The blue, solid line shows a numerical simulation. Areas shaded in gray indicate the relevant absorption ranges to determine the logic output values 0 and 1.

SP pairs, we observe low absorption (as the system or memory is finally driven to state $|0\rangle$). The simulation (blue, solid line in Fig. 3) describes the data well. Small deviations are due to a lack of exact values for laser jitter and residual two-photon detunings. The overall slow reduction of the contrast between high and low absorption is due to optical decay of residual population in the excited state after incomplete transfer by b-STIRAP (compare also Fig. 2). Nevertheless, we clearly observe cyclic transfer for up to eight SP pulses. To apply the above experimental scheme as a logic gate, we define the logical input by SP pairs. The presence of an SP pair defines the logic input 1. The absence of an SP pair defines the logic input 0. The output bit of the gate is defined by the absorption level (high or low), after application of an SP pair. High absorption corresponds to the logic output 1. Low absorption corresponds to the logic output 0. The corresponding absorption ranges are marked in Fig. 3 as gray areas. After each application of an SP pair the output of the gate flips between 0 and 1. Thus, the logic scheme corresponding to Fig. 3 exhibits a STIRAP-driven flip-flop, i.e., a basic finite state logic machine. If we restrict the gate to two subsequent input bits (i.e., two SP pairs), we get output = 1 if exactly one input is 1. This corresponds to a STIRAP-driven optical-cyclic XOR gate in the doped solid.

We extend now the scheme toward a full adder (compare Table I). As before, we define optical input bits by SP pairs, and the sum bit of the adder by high absorption (logic value 1) or low absorption (logic value 0). To obtain the carry-out bit, we detect stimulated emission (i.e., a negative absorption coefficient) of the probe laser. In the case of b-STIRAP, population is transferred via the excited state $|e\rangle$. During the interaction, population inversion occurs between states $|e\rangle$ and $|1\rangle$. The amount of population in $|e\rangle$ increases with smaller single-photon detuning Δ. Therefore, probing sufficiently close (but not exactly on) resonance enables observation of stimulated emission during b-STIRAP, i.e., after an even number of SP pairs. Thus, we tune the probe laser now closer to resonance, i.e., to $\Delta\nu_{\rm pr} = -0.2$ MHz. All other experimental parameters remain unchanged. If we observe stimulated emission during the process, the carry-out bit is 1; otherwise it is 0.

Figure 4 shows the absorption dynamics for a sequence of four SP pairs, which represent the optical input bits. We note that for a full adder (with two output bits) we require only the first three SP pairs, or two SP pairs and the memory. Labels on the figure indicate the number of applied SP pulse pairs. The graph shows fast absorption changes, each time an SP pulse pair interacts with the system. The absorption coefficient drops to negative values after an even number of SP pairs. The negative absorption coefficient defines the logic value 1 in the carry-out bit. To operate the logic machine under realistic conditions, we define ranges of absorption levels to determine the logic values of sum and carry-out bit. These ranges are depicted in Fig. 4 by areas shaded in gray. The logic scheme, deduced from Fig. 4, resembles a full adder (compare Table I), which calculates the binary sum of three optical input bits (or two optical input bits and a memory bit). Thus, the data clearly demonstrate a STIRAP-driven, optical full adder in the doped solid. We note that the slow overall absorption modulation (i.e., the decrease in the contrast) is

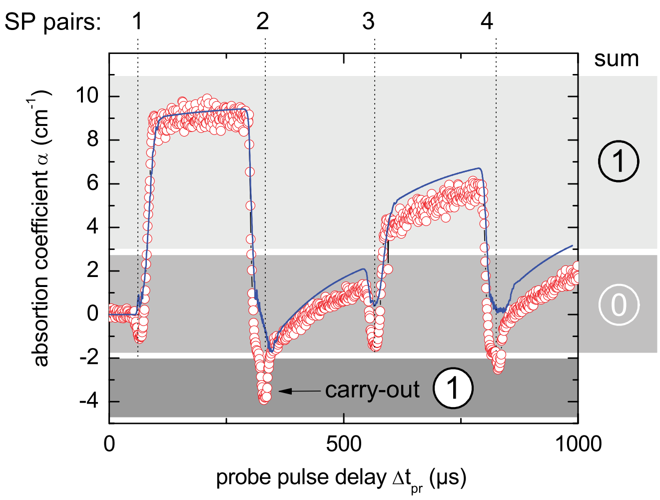

FIG. 4. (Color online) Absorption dynamics in a STIRAP-driven optical full adder. Red, open circles indicate experimental data. The solid, blue line shows a numerical simulation. Areas shaded in gray indicate the relevant absorption ranges to determine the logic output values 0 and 1 for sum and carry-out. Consider, e.g., the dynamics after application of three input bits (i.e., three SP pairs). The system is driven from $|0\rangle$ to $|1\rangle$ by STIRAP, from $|1\rangle$ to $|0\rangle$ by b-STIRAP, and again from $|0\rangle$ to $|1\rangle$ by STIRAP. Thus, the final absorption is high, defining the sum bit = 1. As we observe amplification during the b-STIRAP process, we get the carry-out bit = 1. Thus, the binary sum 1 + 1 + 1 yields (11).

larger compared to the implementation of an XOR gate (see Fig. 3). Due to the smaller detuning, the efficiency of the b-STIRAP processes decreases. This leaves more population in the excited state and causes increasing losses by decay. These losses limit the maximal number of operations to four input SP pairs. This is more than sufficient for the adder with a two-bit output.

III. CONCLUSION

To conclude, we implemented cyclic population transfer in Pr^{3+}:Y_2SiO_5, driven by STIRAP and b-STIRAP. We drove the solid medium from a ground state $|0\rangle$ to a target state $|1\rangle$ by STIRAP. The process involved interaction with a first SP laser pulse pair, tuned close to atomic resonances. A second SP pulse pair drove the medium by b-STIRAP back from state $|1\rangle$ to $|0\rangle$. Observation of absorption in the medium enabled determination of the state of the memory after sequences of SP pulse pairs. The behavior of the memory after excitation by a sequence of SP pulse pairs resembled an optically driven flip-flop or XOR gate. Losses during the transfer processes limited the maximal number of operations to eight. By observation of stimulated emission as an additional output channel, we extended the logic scheme and demonstrated a STIRAP-driven optical full adder to calculate the sum of three optically encoded input bits (or two input bits and a memory bit). In summary, we demonstrated a solid-state optical memory and two-output finite state logic machine, coherently driven by robust STIRAP and b-STIRAP processes, enabling classical processing of optically encoded information. The huge inhomogeneous manifold in a doped crystal may enable optical parallel computing. In our work, we applied off-resonant STIRAP processes—which are well suited to drive ensembles in parallel. This may increase processor rates by orders of magnitude. The processor rate in our experiment is limited by the pulse duration to 100 kHz. Doped crystals with larger level spacing (e.g., Er^{3+}-doped) will permit operation with shorter pulses and rates of 10 MHz. Implementation with picosecond pulses in media of appropriate level structure (i.e., with level spacings exceeding the laser pulse bandwidth) will permit terahertz rates.

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