SAND2012-1926C

Low-Power All-Optical Switching in Si_3N_4 Micro-Resonators with EIT Based Zeno Effect

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Abstract: We present theoretical results of an all-optical switch in a micro-disk resonator cavity using the Zeno effect and electromagnetically induced transparency (EIT). We predict a switching contrast of over 20 dB with only 100 nW of control-beam power.

OCIS codes: 250.6715, 270.1670.

1. Introduction

The quantum Zeno effect (QZE) was first coined by Misra and Sudarshan [1]. It is process whereby frequent measurements of a quantum system can inhibit quantum transitions from taking place. Consider the decay of an atom from an excited state to its ground state. If one were to measure that the atom has not decayed, this would collapse the wavefunction to the excited state. By measuring repeatedly with frequency much greater than the decay rate, one can continuously collapse the wavefunction to the excited state, thereby preventing decay. Thus a null measurement prevents the effect from happening.

It was previously demonstrated that a classical analogue to the QZE could be used to create an all-optical switch using two-photon absorption (TPA) in a resonant optical cavity [2]. The TPA acts to suppress the resonant field buildup which alters the transmission of the system when two input beams are present. When only a single beam is present, the measurement does not occur and the beam couples into the cavity and exits through the opposite waveguide. In this manner a classical all-optical switch can be created using the Zeno effect.

Here we report results from numerical simulations showing that EIT can be used to implement the Zeno effect to create an all-optical switch. We make use of single photon absorption (SPA) to suppress the resonant buildup, and use EIT to turn this suppression on and off to create a switch. We provide results predicting that one can use this technique to obtain a switching contrast in the resonator of 20 dB with a 100 nW control beam.

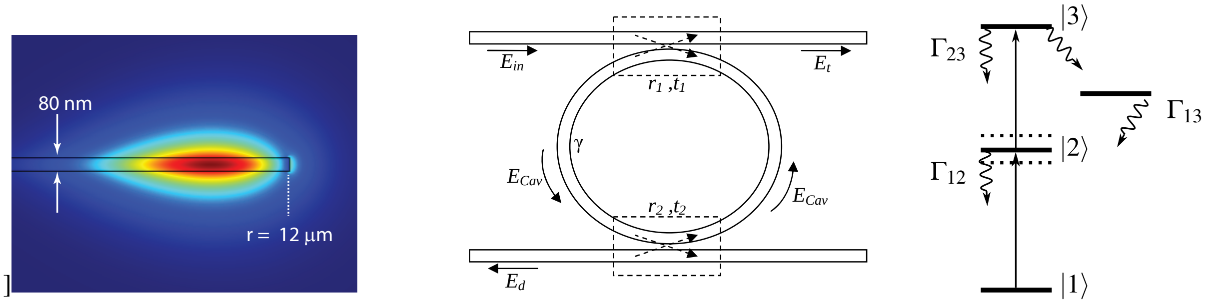
2. Theoretical Model

Our theoretical model combines a quantum optical treatment of two laser fields interacting with a three-level atom, along with a classical electromagnetic treatment of two waveguides coupled to a micro-resonator. We use an electromagnetic simulation of the field-modes of the resonator as an input to the quantum simulation. The field profiles were calculated using a fully vectorial 2-D axially symmetric weighted residual formulation of Maxwell's equations implemented in Comsol Multiphysics software. The absorption coefficient obtained from the quantum simulation is then used to predict the coupling between the waveguides and the resonator, with and without the control field, enabling us to provide estimates for the switching contrast.

The resonator device field profile and schematic is shown in Figs. 1(a) and 1(b) . The microdisk resonator consists of an unclad suspended Si_3N_4 disk (refractive index ≈ 1.98) with a radius 12 μm and a thickness of 80 nm, designed such that the free spectral range of the resonator is approximately equal to the 4 nm splitting between the $5S_{1/2} \rightarrow 5P_{3/2}$ D2 line at 780 nm, and the $5P_{3/2} \rightarrow 5D_{5/2}$ line at 776 nm. This allows for simultaneous resonances at 776 nm and 780 nm. The microdisk thickness of 80 nm is chosen such that roughly 30% of the electric field energy is outside of the resonator, allowing for interaction of the cavity fields with the Rubidium vapor surrounding the cavity.

We model the interaction of the signal beam and a counter-propagating control field with the Hamiltonian

$$H = -\hbar\frac{\Omega_s}{2}|1\rangle\langle 2| - \hbar\frac{\Omega_c}{2}|2\rangle\langle 3| - \hbar\frac{\Omega_s^*}{2}|2\rangle\langle 1| - \hbar\frac{\Omega_c^*}{2}|3\rangle\langle 2| + \hbar\Delta_s|1\rangle\langle 1| - \hbar\Delta_c|3\rangle\langle 3|, \quad (1)$$



(a) (b) (c)

Fig. 1. (a) Simulated electric field profile of the microdisk. Shown is the radial component E_r of the TE-like mode used in the EIT based Zeno switching calculation. (b) The four-port resonator design of the SiN microdisk. In the absence of a control beam the signal, E_{in} does not couple into the resonator and leaves through port E_t. With the control beam on an EIT window is produced, allowing the signal to couple into the resonator and back out through the opposite waveguide leaving through E_d, thus creating an all-optical switch. (c) The three-level atom we use to model the Rubidium vapor. The $|1\rangle \rightarrow |2\rangle$ transition is the $5S_{1/2} \rightarrow 5P_{3/2}$ D2 line at 780 nm, and the $|2\rangle \rightarrow |3\rangle$ transition is the $5P_{3/2} \rightarrow 5D_{5/2}$ line at 776 nm. The presence of the upper control beam slits the intermediate level, eliminating single photon absorption of the signal beam. The fourth level on the right is a decay channel from state $|3\rangle$ to state $|1\rangle$ through the intermediate $6P_{3/2}$ state.

where Δ_s is the detuning of the signal field from the $|1\rangle \rightarrow |2\rangle$ transition and Δ_c is the detuning of the control field from the $|2\rangle \rightarrow |3\rangle$ transition. In our density matrix treatment, we include the homogeneous decay terms indicated in 1(c), and the associated off-diagonal decay terms which we assume to be dominated by homogeneous decay.

To determine how much of the field from the input waveguide couples into the resonator, we must calculate the absorption coefficient for the signal field outside the resonator. This is given by

$$\alpha(\Delta_s) = -2\mu \mathrm{imag}[\chi_{12}(\Delta_s)], \tag{2}$$

where $\chi_{12}(\Delta_s) = \langle \rho_{12}(\Delta_s)/\Omega_s \rangle$ with ρ_{12} the off-diagonal density matrix element connecting states 1 and 2. The angular brackets denote Doppler and field-mode averaging. The coefficient $\mu = 2Nd^2\omega_s/(\hbar\varepsilon_0 c)$, with N the density of atoms, d the dipole moment of the $|1\rangle \rightarrow |2\rangle$ transition, and ω_s the angular frequency of the same transition.

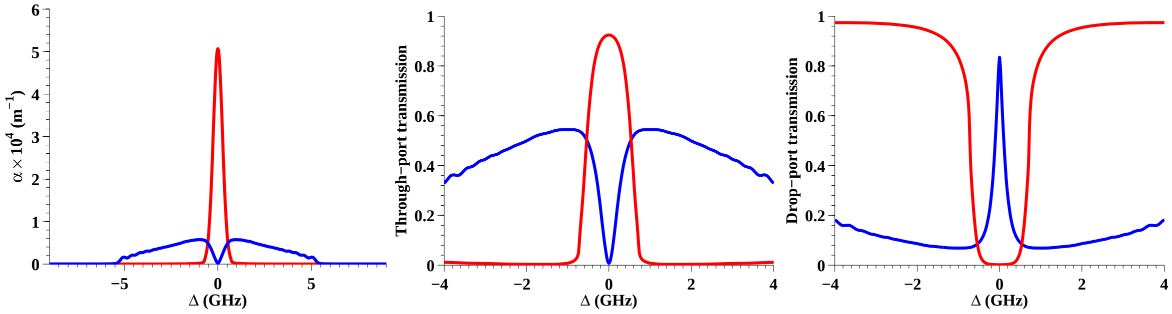
When solving the density matrix equations, we do not make any perturbation assumptions since the high Q resonator can create very intense fields. However, we do assume steady-state conditions by taking the time derivatives to be zero. We numerically solve the system of equations under the initial condition that $\rho_{11}(t=0) = 1$. Our numerical treatment allows us to go beyond the restrictions required to derive an analytic solution [3], and allows us to include realistic decay terms, Doppler broadening, and field-mode averaging.

We include Doppler broadening by averaging over a range of detunings of the two beams, however because the beams are counter-propagating, Doppler broadening plays a minor role. The small mode volume and large quality factor of the resonator produce high intra-cavity intensities for even modest input power levels. This creates large Autler-Townes splitting of the intermediate level. However, the field distribution of the control beam outside the resonator falls off very quickly. This causes the signal beam to see a distribution of EIT windows, rather than a single split line. To capture this, we average over the field distributions of both the signal and control fields outside the resonator.

3. Results

We present results from numerical simulations of the model just discussed. We use numerical values based upon realistic laboratory conditions that we currently use for ongoing experiments. We take the intensity of the control beam to be 10 kW cm^{-2}. This can be achieved in the cavity with only 1 μW of input power. We take the signal beam to have an intensity of 1 mW cm^{-2} corresponding to an input power of about a pW. We estimate the Rubidium atoms surrounding the resonator to have a density of 5×10^{12} cm^{-3}, and a temperature of 100° C. The field profile of the signal and control beams come from an electromagnetic simulation done in *YYYYYY* simulation software.

We plot the absorption coefficient of the signal beam in Fig. 2(a), with the control beam on and off. EIT absorption cancellation is seen when the control beam is turned on. The spectral shape is modified from the typical double-Lorentzian peaks associated with Autler-Townes splitting because of the averaging over the field profile.



(a) (b) (c)

Fig. 2. (a) The absorption coefficient without EIT in red and with EIT in blue (b) Through-port transmission in each case (c) Drop-port transmission in each case

Upon estimating the loss present with and without the control beam, the evolution of the cavity mode field and the resulting transmission of the system is calculated using the basic E&M formalism presented in Ref. [2]. The amount of light that couples into the resonator from the input waveguide is determined by the intra-cavity absorption characteristics due to the evanescent interaction with the Rb atoms.

We can estimate the switching contrast by comparing how much light couples into the resonator with and without the control beam on. We plot the two cases in Figs. 2(b) and 2(c). One can see a substantial reduction in the coupling when the control beam is off, and from this calculation we estimate the switching contrast to be 19.3 dB in the through-port and 27.3 dB in the drop-port.

4. Conclusions

We have presented a technique for a low-power all-optical switch using EIT and the Zeno effect with a micro-resonator. The presence of the strongly absorbing medium, serves to "measure" whether or not light is in the resonator, thereby suppressing resonant buildup in the cavity. We use EIT to modify the strength of this measurement, thereby changing the quality factor of the resonator, which allows us to control the amount of light that couples into it from a nearby waveguide. We predict a switching contrast of greater than 20 dB with only 100 nW of control beam power.

Acknowledgments

Funding for this work was provided in part by internal research and development sources and the DARPA ZOE program (Grant No. XXXXX).

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