Microcavities with Highly Dispersive Materials

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Our detailed theoretical studies show how inserting materials that support electro-magnetically induced transparency into microcavities enables design of microcavities with extraordinarily long lifetimes, and enables all-optical signal processing at single photon power levels.

There are two main approaches that one can pursue in order to achieve optimal non-linear optical response. The first approach is structural, where one aims to find an optimal structure that will (through its geometrical properties) enhance non-linear response. Some of the most promising systems that explore this approach are high quality factor (Q) microcavities [1], especially those in photonic crystals (PhCs) since they enable having small modal volumes, and large Qs, present in the same systems at the same time. The other approach is material-oriented, where one aims to find a material with non-linear response as strong as possible. In that sense, materials that exhibit electro-magnetically induced transparency (EIT) are probably optimal, since non-linearities 12 orders of magnitude stronger than those in GaAs have been measured in such materials [2]. Combining the best of these two worlds (i.e. by placing EIT materials inside of a PhC microcavity), one can obtain structures of unprecedented non-linear response, which might enable observation of non-linear phenomena at single photon power levels [3]. Moreover, placing material as strongly dispersive as EIT into a cavity greatly enhances its life-time [4], so this mechanism could be explored to design microcavities of unprecedented Q values. We present results of our detailed numerical studies(*), and analytical theory on such systems that confirm existence of both of these effects.

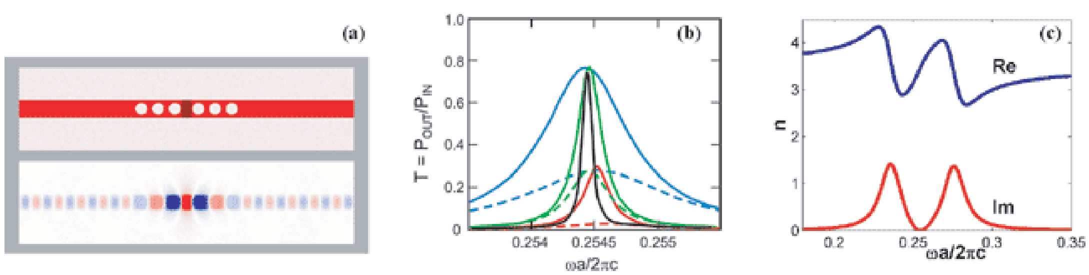

Figure 1: Panel (a): the photonic crystal microcavity system simulated (top): it consists of high-ε=12 (red), surrounded with air; the magnetic field of the confined mode, is perpendicular to the plane everywhere (bottom). The distance between the holes is denoted by a. Panel (b): the transmission curve of the cavity is given by the solid blue line. Imagine next inserting into the central (shaded) region of this cavity a highly dispersive material whose $n(\omega_{RES})$ is exactly the same as the index of the cavity, but whose $n(\omega)$ is given in panel (c). The new transmission is given by the solid green line: the low group velocity makes light take "longer roundtrips" between the mirrors thereby increasing the lifetime. Effectively, dispersion weakens the

coupling of the resonant mode to both the waveguide, and the radiation modes equally. Thus, although one might think that the fact that light spends more time in the cavity gives it more time to interact with the radiation modes (which would increase the radiation losses), this is not the case; a signature of this is the fact that the peak transmission is exactly the same as before. Note that if (instead of inserting dispersion) we try to increase Q by adding one more whole to each side of the cavity, Q will indeed increase, but so will the radiation losses, as is shown by the transmission curve in that case (the solid-red curve), whose peak transmission is now significantly decreased. If we decrease the group velocity by an additional factor of 3 compared to what is shown in panel (c), Q increases by an additional factor of 3 (as shown by the solid black line). In fact, one can show that Q scales roughly as c/v_G [4]. Consider next inserting also a small amount of absorption (Im{ε}=0077}, into the central (shaded) cavity region for each of the cases considered above. The resulting transmissions are shown by the dashed curves above. The peak transmissions of the green, and blue curves decreases by the same amount (meaning that the absorption losses are the same), but the peak transmission of the red curve decreases much more, resulting in a much larger decrease in peak transmission. The way to understand this is to note that since light has much more time to interact with absorptive material in the case of the red curve, than in the case of the blue curve. The same logic cannot be applied for the case of the green curve, since exactly at ω_{RES}, the system with, and without dispersion looks exactly the same; thus at that particular frequency, the transmission has to be the same. Panel (c): material dispersion used in simulations for the solid green curve in panel (b)

Imagine a microresonator, with one input, and one output waveguide, with equal input and output couplings, like the one shown in Fig.1a, with resonant frequency ω_{RES}. As we can see in Fig.1b, insertion of dispersive material (e.g. one shown in Fig.1c) into the cavity can drastically increase its lifetime, without making radiation or absorption losses any worse than before. All the features of Fig.1b can also be explained (to within a few %) using perturbation theory approach [4]. This effect could be used to drastically increase lifetimes of existing microresonators; since group velocities as low as $v_G/c=10^{-7}$ have been observed [2], Q enhancement factors as large as 7 orders of magnitude can be envisioned. Microresonators of such large Qs could have many interesting applications including maybe for integrable atomic clocks.

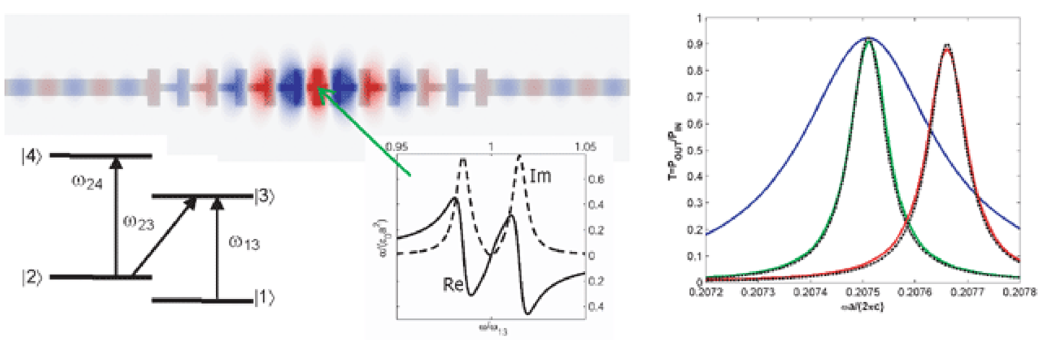

Figure 2: The photonic crystal microcavity system simulated is shown in upper-left panel: it consists of high-ε =12 (grey), surrounded with air; the electric field of the confined mode, is perpendicular to the plane everywhere. The horizontal periodicity of the grating is denoted by a. Transmission through this cavity (when EIT atom is not present) is given by the blue curve in the panel on the right. The polarizability of the central EIT atom (with levels shown in bottom-left panel, and all population in level |1> initially), is shown in center-bottom panel; the presence of the field with frequency ω_{23} introduces a narrow transparency window for frequencies which are close to ω_{13}. The large dispersion due to EIT narrows the transmission spectrum (as shown by the green curve in the right panel. Next, we consider applying a field of frequency ω_{24} to the system; since it is an on-resonant field, it causes a strong Stark shift of level |2>, thereby moving the whole transmission curve side-ways as shown by the red curve in the right panel. Since the resonance is so narrow, the shift required to move the curve by more than its width (i.e. to switch it on-off) is very small. The results of our analytical theory [3] are given by the dashed black lines in the right panel, and they agree very well with the corresponding numerical results.

Next, we simulate a cavity similar to the one in Fig.1a, but this time instead of placing uniform dispersive EIT medium in the central region of the cavity, we place a single EIT atom (of dipole moment **p**) in the center of the cavity. (In the particular scenario shown here, all EIT fields (ω_{13}, ω_{24}, and ω_{23}) are resonant with the single mode of the cavity; nevertheless, many other geometries are possible.) One can show [3] that thi system behaves the same as the system that contains uniform dispersive medium of $\mathbf{P}=\mathbf{p}/V_{MODE}$, where V_{MODE} is the modal volume of the cavity. Because of the small modal volume, the effective atomic density turns out to be comparable to the one from Ref. [2], so even a single atom causes a large effect. The results of the simulations are shown in Figure 2. The combination of on-resonant non-linear effects (i.e. on-resonant Stark shifts) together with very narrow resonance lines enables all-optical switching at very low power levels. For example, using parameters of the sodium atom [2], and λ_{RES}=589nm, one can show that the power in ω_{24} needed to switch ω on-off is as low as P_{24}~4μ W, meaning that having only ~11 ω_{24}-photons in the cavity a any given time could switch the cavity from its on-state into its off-state; the available bandwidths for ω_{24}, and ω in this particular example would be >10GHz. By exploring ever narrower bandwidths, one could approach the single-photon regime, which could have useful applications for all-optical quantum information signal processing.

Acknowledgements
* We simulate Maxwell's equations exactly with no approximation, apart for the discretization; such simulations are known to be able to reproduce exact (quantitative) experimental results very accurately. In order to save on computational resources, we simulate 2D models; the physics of 3D systems will be the same.

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