EIT in resonator chains: similarities and differences with atomic media

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We theoretically study a parallel configuration of two interacting whispering gallery mode optical resonators and show a narrow-band modal structure as a basis for a widely tunable delay line. For the optimum coupling configuration the system can possess an unusually narrow spectral feature with a much narrower bandwidth than the loaded bandwidth of each individual resonator. The effect has a direct analogy with the phenomenon of electromagnetically induced transparency in quantum systems where the interference of spontaneous emission results in ultra-narrow resonances.
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Recent applications of electromagnetically induced transparency (EIT) [1, 2] in ultra-cold and room temperature atomic vapors have led to the observation of phenomena of "slow" and "stored" light [3, 4]. Practical photonic applications of EIT for filtering and delays in optical signal processing are nonetheless hindered by the limitations due to the specific light wavelengths corresponding to appropriate atomic transitions, as well as the residual intrinsic absorption of the atomic systems. The achievable width of the EIT is limited to narrow resonances with corresponding delays in the micro-second range. Tunable delays in the range of nanoseconds required in a number of practical applications cannot be easily obtained with EIT in atomic vapors.

In this paper we demonstrate an application of cascaded resonators for real-time shaping of their modal structures. Our interest is in whispering gallery mode (WGM) resonator systems that mimic narrow linewidths obtained with EIT. A key feature of our approach is that it points to a simple tuning of the frequency and the width of the resonator system "EIT" resonance, allowing the tuning of the delay of optical signals, a highly desirable feature for signal processing applications. The cascaded WGM resonators offer a number of other important advantages over atomic vapors and doped solids to make practical applications feasible.

Slow light in chains of coupled resonators have been previously studied [5, 6]. It was also predicted that an optical double-cavity resonator may have a response similar to that of EIT effect in atomic vapor if the quality factor of one resonator significantly exceeds quality factor of the other resonator [7]. Existing of a narrow spectral feature was demonstrated in a set of two coupled WGM resonators [8]. Those schemes, however, have been exclusively applied to the case of fixed, non-tunable, resonances.

It is known that the quantum mechanical interference of the spontaneous emission from two close energy states coupled to a common ground state results in EIT [9, 10]. Our work produces results similar to that picture, but based on classical cavity modes. The origin of the phenomenon in our case is the interference between direct and (a resonance assisted) indirect pathways for the two cavities' decays. This is the same Fano resonance for optical resonators, which has been shown to result in sharp asymmetric line shapes in a narrow frequency range in periodic structures and waveguide-cavity systems [11, 12].

Below we analyze a parallel configuration of two WGM resonators [13–15], shown in Fig. (1a), leading to subnatural (i.e. narrower than loaded), EIT-like linewidths. We discuss the applications of such a device as slow light element, which can take advantage of recent demonstration of WGM in crystalline resonators to provide frequency and bandwidth tuning capabilities [16]. An additional result of our analysis is that the system of two coupled WGM resonators can be reconfigured (see Fig. (1b) to produce a third order filter function. This is in contrast to previous studies that obtained a second order filter function by cascading two WGM resonators.

We find the transmission coefficient for configuration shown in Fig. (1a):

$$T_P = \frac{[\gamma + i(\omega-\omega_1)][\gamma + i(\omega-\omega_2)]}{[2\gamma_c + \gamma + i(\omega-\omega_1)][2\gamma_c + \gamma + i(\omega-\omega_2)] - 4e^{i\psi}\gamma_c^2}, \quad (1)$$

where γ, γ_c, ω_1, and ω_2 are the linewidth originated from intrinsic cavity losses, linewidth due to coupling to a waveguide, and resonance frequencies of modes of the resonators, ω is carrier frequency of the light (we assume that $|\omega-\omega_1|$ and $|\omega-\omega_2|$ are much less than the cavity free spectral range); ψ stands for the coupling phase, which may be adjusted by changing the distance between the cavities [8, 17]. Choosing $\exp i\psi = 1$ and assuming strong coupling regime $\gamma_c \gg |\omega_1-\omega_2| \gg \gamma$ we see, that the power transmission $|T_P|^2$ has two minima

$$|T_P|^2_{min} \simeq \frac{\gamma^2}{4\gamma_c^2}$$

for $\omega = \omega_1$ and $\omega = \omega_2$, and a local maximum

$$|T_P|^2_{max} \simeq \frac{(\omega_1-\omega_2)^4}{[16\gamma\gamma_c + (\omega_1-\omega_2)^2]^2}$$

for $\omega = \omega_0 = (\omega_1+\omega_2)/2$. The transmission is shown in Fig. (2). It is important to note that for $\gamma = 0$, the width

of the transparency feature Γ may be arbitrarily narrow:

$$\Gamma \simeq \frac{[16\gamma\gamma_c + (\omega_1 - \omega_2)^2]^2}{16\gamma_c(\omega_1 - \omega_2)^2}. \quad (2)$$

The group time delay originated from the narrow transparency resonance is approximately $\tau_g \approx \Gamma^{-1}$. Therefore, the system could serve as an efficient "source of slow light" [3].

The origin of this "subnatural" structure in the transmission spectrum of the cavities is in the interference of the cavities' decays. In fact, in the overcoupled regime we consider here, the cavities decay primarily into the waveguides, and not into free space. Thus there are several possible paths for photons transmitted through the cavities, and the photons may interfere because they are localized in the same spatial configurations determined by the waveguides. The transmission is nearly cancelled when the light is resonant with one of the cavities' modes. However, in between the modes the interference results in a narrow transmission resonance. This phenomenon is similar to EIT originating from the decay interference, predicted theoretically in [10].

The resonator compound delay line has several advantages over similar atomic, "slow light", systems. For example: i) The resonator delay time depends on the frequency difference $\omega_1 - \omega_2$. Tuning this difference simply tunes the delay time. The tuning may be accomplished very easily, for example, by using resonators made with electro-optic crystals [16]. The delay time corresponds to linewidth of the filter which could be changed from hundreds of kiloHertz to several GigaHertz. This is impractical to achieve in atomic vapors because it will require a very high intensity for the drive laser. ii) The frequency of the "transparency window" of the resonator system $((\omega_1 + \omega_2)/2)$ is arbitrary, while in atomic systems the EIT signal is limited only to a small number of accessible transition frequencies. This is an important advantage for the cascaded WGM resonators for applications in optical signal processing and optical communications. iii) The resonator systems have much lower losses than atomic ones. Real atomic systems absorb a significant amount of light since spontaneous emission is not fully suppressed. iv) To create EIT in an atomic vapor a powerful drive laser should be used. In the case of cavities no drive power is needed. Therefore the cavities will consume much less power compared with atomic vapors. v) The size of the atomic systems is dictated by the size of the atomic cells that are at centimeter scaler, while WGM cavities can be in the sub-millimeter scale.

We should point out that the cavity considered in Ref.[11] is different from the WGM resonators because it results in a reflection of light, while WGM resonators introduce no reflection into the input waveguide. It is thus interesting to see how the configuration discussed in Ref.[11] changes if a WGM cavity is used there. We consider a waveguide side coupled to a WGM resonator. Two partially reflecting elements are incorporated into the waveguide (see in Fig. 1c). The response of the system is described by amplitude transmission (T_w) coefficient

$$T_w = \frac{(1 - r^2)T_L \exp[i\psi_r/2]}{1 - T_L^2 r^2 \exp[i\psi_r]}, \quad (3)$$

where r is the amplitude reflectivity of the waveguide reflection elements, $\psi_r = 2\omega n_r L/c$ is the phase shift that the waveguide mode acquires as it propagates with phase velocity c/n_r a distance L between the partially reflecting elements, and T_L is an amplitude transmission coefficient for a mode of single WGM cavity with frequency ω_0

$$T_L = \frac{\gamma_c - \gamma - i(\omega - \omega_0)}{\gamma_c + \gamma + i(\omega - \omega_0)}. \quad (4)$$

If critical coupling ($\gamma_c = \gamma$) is realized the transmission and reflection coefficients have spectral features on the order of γ. On the other hand, even if $\gamma_c \gg \gamma$ and $\gamma_r, \gamma_c \gg (1 - r^2)\gamma_c \sim \gamma$, the narrow absorption feature can still be observed in the system.

Using these results we could draw a general conclusion. Coupling of optical resonators allows for the realization of narrow spectral features. The width of such features is limited from below by the intrinsic absorption/scattering in the resonator material, although the feature could be much narrower than the spectral width of each particular loaded resonator. This statement is valid not only for the system of a pair of coupled resonators, but also for the majority of chains of coupled resonators.

Finally, coupled resonators can also serve as high order optical filters, subject to the proper coupling between the resonators. The most complicated coupling configuration of the resonators considered in the paper occurs when parallel resonators as in Fig.(1a) are placed close enough to have a nonzero side-coupling Fig.(1b). We found that a filter based on this system can have a third order response, i.e. the filter amplitude transmission/reflection decrease as fast as the third power of the detuning from the central filter frequency. This unusually increased order filter function arises from the presence of two degenerate modes in each ring cavity. The system of two cavities becomes equivalent to the system of four coupled cavities when all those four modes are coupled (see the equivalent scheme in Fig. (1b)). The narrow spectral feature is absent in this configuration because of our choice of coupling phase $\psi = \pi/2$ (see, e.g. [8]).

This observation extends the results of previous studies that shown systems of WGM resonators coupled in parallel or in series produce a passband that is nearly flat, and result in a second order filter function with two coupled ring cavities [13–15]. The high order filter proposed here has much flatter passband and a sharper rolloff than a filter based on a single resonator, which has a Lorentzian transfer function, or the second order filters proposed in the earlier studies.

In conclusion, we have shown theoretically that two coupled WGM ring resonators could generate modal structures that are much narrower that the spectral

bandwidth of each loaded resonator taken alone. This property would be very important for practical optical and photonic applications such as tunable filters, delay lines, and arbitrary wave form generators. This classical system closely emulates the phenomenon of electromagnetically induced transparency predicted for quantum systems.

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Figures

Fig.1 Configurations of two WGM resonators and their ring-cavity equivalent schemes: (a) resonators coupled in parallel; (b) mixed series/parallel WGM resonator coupling; (c) WGM cavity interacting with a waveguide with partial reflectors.

Fig.2 Power transmission coefficient for two cavities coupled as shown in Fig. (1c). Solid line describes case when $\gamma/2\gamma_c = 5 \times 10^{-4}$ and $(\omega_1 - \omega_2)/2\gamma_c = 0.1$, and dashed line describes case when $\gamma/2\gamma_c = 5 \times 10^{-4}$, $(\omega_1 - \omega_2)/2\gamma_c = 0.5$. Frequency ω_0 corresponds to central frequency $(\omega_1 + \omega_2)/2$.

Fig.3 Power transmission and reflection coefficients for two identical cavities with frequency ω_0 coupled as shown in Fig. (1b). Coupling between the cavities as well as between the cavities and the waveguides is taken to be equal and is characterized by coefficient γ_c. The absorption is neglected. T_L stands for Lorentzian transmission profile. T_1, T_2 stand for transmission, and R_1, R_2 stand for reflection in the two-cavity system.

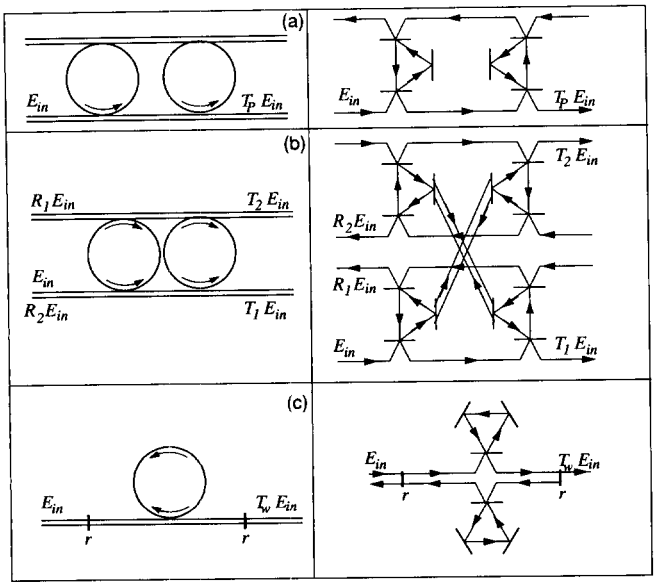
(a)
E_{in}
$T_P E_{in}$
E_{in}
$T_P E_{in}$
(b)
$R_1 E_{in}$
$T_2 E_{in}$
E_{in}
$R_2 E_{in}$
$T_1 E_{in}$
$T_2 E_{in}$
$R_2 E_{in}$
$R_1 E_{in}$
E_{in}
$T_1 E_{in}$
(c)
E_{in}
$T_w E_{in}$
r
r
E_{in}
$T_w E_{in}$
r
r

FIG. 1:

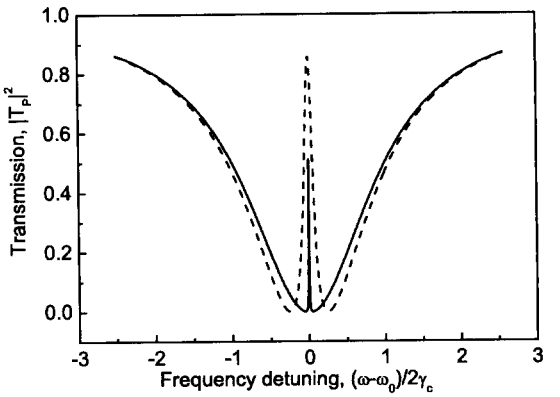
Transmission, $|T_{pl}|^2$
1.0
0.8
0.6
0.4
0.2
0.0
-3
-2
-1
0
1
2
3
Frequency detuning, $(\omega-\omega_0)/2\gamma_c$

FIG. 2:

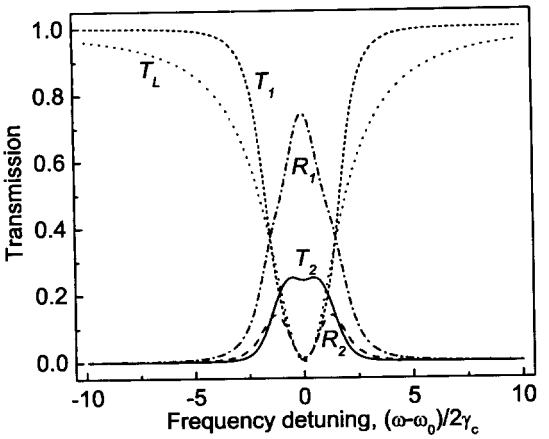
1.0
0.8
0.6
0.4
0.2
0.0
Transmission
T_L
T_1
R_1
T_2
R_2
-10
-5
0
5
10
Frequency detuning, $(\omega-\omega_0)/2\gamma_c$

FIG. 3: