Tunable delay line with interacting whispering-gallery-mode resonators

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We theoretically study a parallel configuration of two interacting whispering-gallery-mode optical resonators and show a narrowband 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 for which the interference of spontaneous emission results in ultranarrow resonances. © 2004 Optical Society of America

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Recent applications of electromagnetically induced transparency[1,2] (EIT) in ultracold and room-temperature atomic vapors have led to the observation of the phenomena of so-called slow and stored light.[3,4] Practical photonic applications of EIT for filtering and delays in optical signal processing are nonetheless hindered by limitations that are due to the specific light wavelengths that correspond to appropriate atomic transitions as well as to the residual intrinsic absorption of the atomic systems. The achievable width of the EIT is limited to narrow resonances with corresponding delays in the microsecond range. The tunable delays in the range of nanoseconds that are required in a number of practical applications cannot be easily obtained with EIT in atomic vapors.

In this Letter we theoretically demonstrate an application of cascaded resonators for agile manipulation of optical signals. Our interest is in whispering-gallery-mode (WGM) resonator systems that mimic the narrow linewidths obtained with EIT. A key feature of our approach is that it points to simple tuning of the frequency and the width of the resonator system's EIT resonance, permitting the controllable delay of optical signals—a highly desirable functionality 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 was studied previously.[5,6] Also, it was predicted that an optical double-cavity resonator may have a response similar to that of the EIT effect in atomic vapor if the quality factor of one resonator significantly exceeds the quality factor of the other resonator.[7] The existence of a narrow spectral feature was demonstrated in a set of two coupled WGM resonators.[8] Those schemes, however, have been applied exclusively to fixed, nontunable 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 similar results but is based on classic cavity modes. The origin of the phenomenon in our case is the interference between direct and (resonance assisted) indirect pathways for the two cavities' decays. This is the same Fano resonance for optical resonators that 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 the parallel configuration of the two WGM resonators[13–15] shown in Fig. 1(a) that lead to subnatural (i.e., narrower than loaded) EIT-like linewidths. We discuss the applications of such a device as a slow light element, which can take advantage of the recent demonstration of WGMs 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. 1(b)] 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.

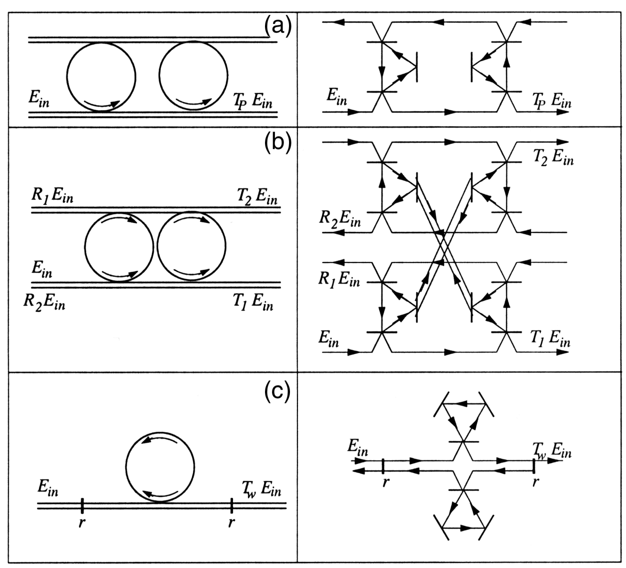

Fig. 1. Configurations of two WGM resonators and their ring-cavity equivalent schemes: (a) resonators coupled in parallel, (b) mixed series–parallel WGM resonator coupling, (c) WGM cavity interacting with a waveguide with partial reflectors.

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

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

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

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

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

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

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 that originated from the narrow transparency resonance is approximately $\tau_g \approx \Gamma^{-1}$. Therefore the system can serve as an efficient source of slow light.[3]

The origin of this subnatural structure in the transmission spectrum of the cavities lies in the interference of the cavities' decays. In fact, in the overcoupled regime that 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 canceled when the light is resonant with one of the cavities' modes. However, between the modes the interference results in a narrow transmission resonance. This phenomenon is similar to that of EIT originating from the decay interference, predicted theoretically in Ref. 10.

The resonator's compound delay line has several advantages over similar atomic, slow light systems. For example, (i) The resonator's delay time depends on frequency difference $\omega_1 - \omega_2$. Tuning this difference simply tunes the delay time. The tuning may be accomplished easily, for example, by use of resonators made from electro-optic crystals.[16] The delay time corresponds to linewidth of the filter, which can be changed from hundreds of kilohertz to several gigahertz. It is impractical to achieve such a change in atomic vapors because that would require a high intensity for the drive laser. (ii) The frequency of the transparency window of the resonator system $[(\omega_1 + \omega_2)/2]$ is arbitrary, whereas 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 systems. Real atomic systems absorb a significant amount of light because spontaneous emission is not fully suppressed. (iv) To create EIT in an atomic vapor, one should use a powerful drive laser. In cavities, no drive power is needed. Therefore cavities will consume much less power than atomic vapors. (v) The size of the atomic system is dictated by the size of the atomic cells, which is on a centimeter scale, whereas WGM cavities can be on a submillimeter 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, whereas 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 [Fig. 1(c)]. The response of the system is described by amplitude transmission (T_w) coefficient

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

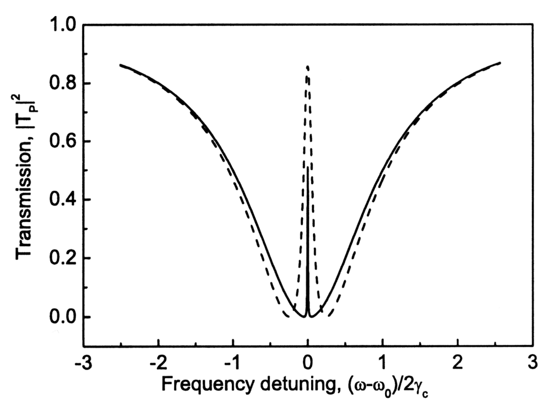

Fig. 2. Power transmission coefficient for two cavities coupled as shown in Fig. 1(c). Solid curve, $\gamma/2\gamma_c = 5 \times 10^{-4}$ and $(\omega_1 - \omega_2)/2\gamma_c = 0.1$; dashed curve, $\gamma/2\gamma_c = 5 \times 10^{-4}$ and $(\omega_1 - \omega_2)/2\gamma_c = 0.5$. Frequency ω_0 corresponds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

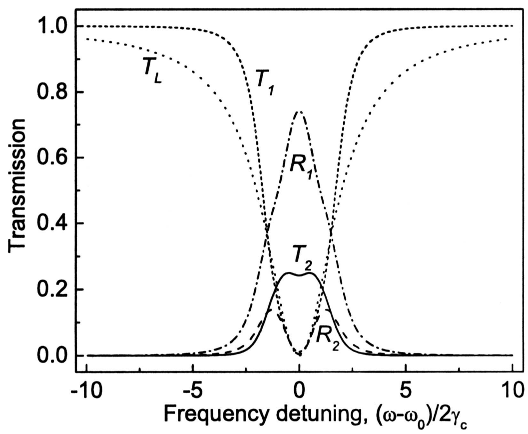

Fig. 3. Power transmission and reflection coefficients for two identical cavities with frequency ω_0 coupled as shown in Fig. 1(b). Coupling between the cavities as well as between the cavities and the waveguides is taken to be equal and is characterized by coefficient γ_c. Absorption is neglected. T_L,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

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 the mode of single WGM cavity with frequency ω_0:

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

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

Using these results, we can draw a general conclusion. Coupling of optical resonators allows for the attainment of narrow spectral features. The width of such features is limited from below by the intrinsic absorption or scattering in the resonator material, although the feature could be much narrower than the spectral width of each 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 proper coupling between the resonators. The most complicated coupling configuration of the resonators considered here occurs when parallel resonators as in Fig. 1(a) are placed close enough to have a nonzero side coupling [Fig. 1(b)]. We found that a filter based on this system can have a third-order response; i.e., the filter's amplitude transmission and reflection decrease as fast as the third power of the detuning from the central filter frequency (see Fig. 3). 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. 1(b)]. The narrow spectral feature is absent from this configuration because of our choice of coupling phase $\psi = \pi/2$ (see, e.g., Ref. 8).

This observation extends the results of previous studies that showed that 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 a much flatter passband and a sharper roll-off than a filter based on a single resonator, which has a Lorentzian transfer function, or than the second-order filters proposed in earlier studies.

In conclusion, we have shown theoretically that two coupled whispering-gallery-mode ring resonators can generate modal structures that are much narrower than the spectral bandwidth of each loaded resonator taken alone. This property will be important for practical optical and photonic applications such as tunable filters, delay lines, and arbitrary waveform generators. This classic system closely emulates the phenomenon of electromagnetically induced transparency predicted for quantum systems.

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