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Comb spectra and coherent optical pulse propagation in a size-imbalanced coupled ring resonator

Ryuta Suzuki, Makoto Tomita*

Department of Physics, Faculty of Science, Shizuoka University, 836, Ohya, Suruga, Shizuoka 422-8529, Japan

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ABSTRACT

Transmission spectra and coherent optical pulse propagation though a size-imbalanced coupled ring resonator are investigated, where the size of the first ring is extremely large and has a narrow free-spectral-range with an extremely high Q-value, and the second ring is small with a moderate Q-value. The system shows characteristic comb spectra due to interference effects between the two resonators. When an arbitrary-shaped coherent pulse propagates through this system, a series of oscillating output pulses appears. It is shown that this pulse train develops into coherent 0π optical pulses.

1. Introduction

Optical resonators have been highly significant in optics and photonics. The high spectral selectivity provided by resonators has been used in spectroscopic applications, and their ability to enhance light–matter interactions demonstrates their potential in nonlinear optics, as well as quantum manipulation of photons [1]. Besides traditional applications, there have also been a number of new developments; optical-mechanical phenomena in micro cavities [2,3], interaction-free measurements in optical resonators [4], and perfect absorption in critically coupled resonators [5] are examples where the unique properties of resonators have been used.

When two resonators are coupled, interference effects provide further interesting and important characteristics. For example, coupled-resonator-induced transparency (CRIT) has attracted extensive interest. A coupled resonator can be described as analogous to a Λ-type three-level atomic system [6–8] and exhibits similar effects to electromagnetically induced transparency (EIT) in atoms [9]. Slow-light propagation [10] has been investigated using CRIT. When more resonators are directly chained, the system is referred to as a coupled resonator optical waveguide (CROW) [11]. This architecture has been realised in many different material platforms and various types of CROW have been proposed. They were conceived as a new technology for integrated devices, demonstrating potential in applications such as Sagnac effects [12], slow or stopped light, optical switching [13].

Here, we discuss an unusual coupled resonator, where the size of the first ring is extremely large, providing a narrow free-spectral-range (FRS) with an extremely high Q-value [10^{10}], and the second ring is small with a moderate Q-value [10^8]. Fig. 1(a) shows schematic illustration of the size-imbalanced coupled resonator, where R_1 and R_2 are the large and small rings, respectively. Our motivation is illustrated schematically in Fig. 1(b). Recognizing the first ring as a feedback loop, we reconfigured the system (Fig. 1(a)) as a serial array of identical ring resonators (Fig. 1(b)). In contrast to CROW systems, the resonance frequency and Q-value of the resonators in the equivalent system of the serial array of resonators can be set to be identical. Using this system, we can investigate the propagation of pulses through a serial array of identical ring resonators. We investigated transmission spectra and coherent optical pulse propagation through the system. The spectra showed a characteristic comb structures due to the interference effect between the first and second resonators. When coherent optical pulses propagate through this system, a series of oscillating pulse trains appeared, related to the spectral comb structures. It is shown that this pulse train develops into coherent 0π optical pulses. That is, the pulse area, defined by the time integral of the slowly varying envelope of the electric fields, decayed exactly exponentially to 0π during propagation, independently of the input pulse duration or the input pulse shape, thus strictly obeying the McCall and Hahn [14,15] pulse area theorem in a linear regime [16–19]. The unique feature of the weak coherent 0π pulse is that the decay of the pulse area does not necessarily imply that the pulses lose their energy. The slowly varying electric field envelope oscillates between positive and negative values in such a way that the area theorem is satisfied. Recently, the development of coherent 0π pulses has been demonstrated successfully in a ring resonator with a dynamic recurrent loop [20]. In this dynamic system, a fast optical switch was employed and optical pulses were injected into the dynamic recurrent loop. Pulse states were examined after passing through resonators an arbitrary number of times. The

* Corresponding author.

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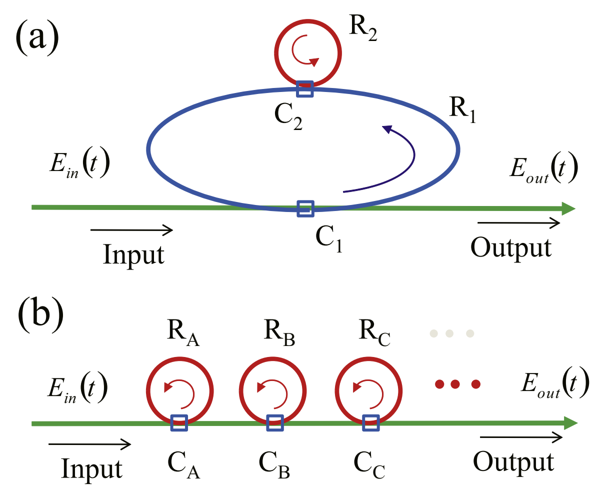

Fig. 1. (a) Schematic illustration of the size-imbalanced coupled resonator. C_1, and C_2 are couplers. R_1 (blue line) and R_2(red line) are the large and small rings, respectively. (b) Illustration of a conceptual serial array of ring resonators where R_A,R_B,R_C,...are ring resonators with the same resonance frequency and C_A,C_B,C_C,.., are couplers.

present coupled resonator could be reorganised as a static version of the above dynamic system. The differences between the present static system and the dynamic system are briefly discussed.

2. Size imbalanced coupled resonator and transmission spectra

Before the analysis of coherent optical pulse propagation, we first describe the steady state transmission spectra. Fig. 1(a) shows a schematic illustration of the coupled ring resonator, where the first ring R_1 is large with an extremely high Q-value and the second ring R_2 is small with a moderate Q-value. The steady-state output of the electric field, $E_{out}(\omega)$, normalised by the incident light electric field $E_{in}(\omega)$, is described in a similar manner to conventional coupled resonators [21],

$$\frac{E_{out}(\omega)}{E_{in}(\omega)} = \mathrm{Res}(\omega) = \sqrt{T(\omega)}\exp[i\theta(\omega)],$$

where

$$\mathrm{Res}(\omega) = (1-\gamma_1)^{1/2}\left[\frac{y_1 - x_1R_2(\omega)\exp[i\varphi_1(\omega)]}{1 - x_1y_1R_2(\omega)\exp[i\varphi_1(\omega)]}\right]$$
$$R_2(\omega) = (1-\gamma_2)^{1/2}\left[\frac{y_2 - x_2\exp[i\varphi_2(\omega)]}{1 - x_2y_2\exp[i\varphi_2(\omega)]}\right] \tag{1}$$

ω is detuning frequency from the resonance of R_1 and R_2, $x_i = (1-\gamma_i)^{1/2}\exp(-\rho_iL_i/2)$ and $y_i = \cos(\kappa_i)$ are the loss and coupling parameters, respectively, ρ_i is the roundtrip loss, κ_i is the coupling strength, and γ_i is the excess loss. $\varphi_i(\omega) = \omega nL_i/c$ is the phase shift in the circulation orbit, L_i is the length of the ring resonator and n is the effective refractive index, i=1, 2 indicates the first and second resonators, respectively [21]. Note that smaller values of x and y indicate stronger attenuation and stronger coupling, respectively. In the present coupled resonator, we consider a situation where the first ring is large and the free spectral range of the first ring FSR_1 satisfies the relationship $FSR_1 < \delta\nu_2$, where $\delta\nu_2$ is the resonance bandwidth of the second ring R_2. When the ring R_2 is decoupled, i.e. $y_2 = 1$, the bottom T_{bottom} and top T_{top} of the comb appear when R_1 is on- resonance and off-resonance, respectively and obtained from Eq. (1) as

$$T_{bottom} = (1-\gamma_1)\frac{(x_1-y_1)^2}{(1-x_1y_1)^2}$$
$$T_{top} = (1-\gamma_1)\frac{(x_1+y_1)^2}{(1+x_1y_1)^2} \tag{2}$$

When the ring R_2 is coupled, the transmission spectra are modulated by the resonance of the second ring, and exhibit a characteristic comb structure. We categorize the transmission spectra in four cases, case [1], [II], [III], and [IV], depending on the coupling conditions in R_1 and R_2. For convenience, we introduce a renormalized loss parameter for R_1:

$$\bar{x}_1(\omega) = x_1 + R_2(\omega). \tag{3}$$

The renormalized loss includes the loss and phase shift from the resonance R_2. In Case [I], the coupling conditions for both R_1 and R_2 are under-coupling conditions, i.e. $x_1 < y_1$ and $x_2 < y_2$. Fig. 2(a) shows the transmission spectrum for this case. The inherent loss of R_1 is strong compared with the relevant coupling. As the frequency of the incident light approaches the resonance of R_2, $\bar{x}_1(\omega)$ decreases. The coupling of R_1 further departs from critical coupling, i.e. $\bar{x}_1(\omega) << y_1$, which results in an increase in T_{bottom}. This means that the depth of the resonance comb becomes shallow around the resonance frequency of R_2. As a result, the bottom of the envelope function of the comb exhibits a "Λ"-shaped structure (Fig. 2(a1)). The comb is on resonance at ω=0; that is, one of the dips in the comb is centred at $\delta\omega$=0 (Fig. 2(a2)). Similarly, the top of the envelope function shows a shallow dip structure around the resonance of R_2 because T_{top} in Eq. (2) decreases as the frequency of the incident light approaches the resonance of R_2. Fig. 2(b) shows the transmission spectra in case [II], where the coupling conditions for R_1 and R_2 correspond to under-coupling and over-coupling conditions, respectively; $x_1 < y_1$ and $x_2 > y_2$. A "Λ"-shaped transmission spectrum similar to that in Fig. 2(a1) is obtained. In this case, however, the comb is off resonance at ω=0, i.e. ω=0 is located at the middle of the neighbouring two dips of the comb (Fig. 2(b2)). This occurs because the phase is π rad-shifted when the electric field transmits through the over-coupled R_2.

Next, we consider cases [1II] and [IV], where R_1 is prepared in the over-coupling condition, i.e. $x_1 > y_1$. In contrast to the previous cases of [I] and [II], when the incident light frequency approaches the resonance of R_2, the coupling of R_1 approaches critical coupling. The depth of the resonance comb increases around the resonance of R_2. There are two cases. First, when $\bar{x}_1(\omega = 0) > y_1$, the bottom of the envelope function of the comb exhibits a "V"-shaped structure (Fig. 2(c1)). For the second case, $\bar{x}_1(\delta\omega = 0) < y_1$, the bottom of the envelope function of the comb exhibits a "W"-shaped structure (Fig. 2(d1)). This "W"-shaped structure appears because R_1 passes the critical coupling condition, i.e. $\bar{x}_1(\omega) = y_1$, twice when the frequency is increased across the resonance of R_2. The frequency corresponding to the critical coupling conditions are denoted as w_0 in Fig. 2(d1). In case [III] when R_2 is in the under-coupling condition, the comb is off resonance at ω=0. In case [IV] when R_2 is in the over-coupling condition, the comb is on resonance at ω=0. Therefore, regarding the coupling condition of R_2, a reversed relationship compared to cases [I] and [II] is observed. Fig. 2(c) and (d) show examples of the transmission spectra for cases [III] and [IV], where "V" and "W"-shaped structures appear.

3. Coherent pulse propagation and 0π pulse

We analyse the coherent optical pulse propagation through the size-imbalanced coupled ring resonator. Arbitrary-shaped coherent pulses that propagate through this system transform in a series of oscillating output pulses in a train caused by the comb structures, and the pulse train develops into a weak coherent 0π optical pulse. We denote the slowly varying envelope of the electric field of the pulse of input and output light as $E_{in}(t)$ and $E_{out}(t)$, respectively. The Fourier transforms