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A high sensitivity optical gyroscope based on slow light in coupled-resonator-induced transparency

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ABSTRACT

We designed ring-in-ring planar resonator which is coupled with a straight waveguide to yield coupled-resonator-induced transparency (CRIT). The model shows an obvious effect which has a direct analogy with the phenomenon of the electromagnetically induced transparency in quantum systems. Based on this structure, a high sensitive optical gyroscope for measuring absolute rotation is proposed and analyzed. Its sensitivity scales directly with the group index whose can be reached to 10^2–10^4 orders of magnitude by using proper parameters.

1. Introduction

Since slow light was discovered in electromagnetically induced transparency (EIT) [1], it has been widely investigated in many materials and structures (e.g., atomic vapor [2–5], photorefractive crystal [6,7], ruby [8,9], optical fiber [10] and coupled-resonator structure [11–15]) because it has potential application in various aspects, such as all-optical buffer, optical delay line, synthetic aperture radar and optical gyroscope. The concept of slow-light gyroscope was originally proposed by Leonhardt and Piwnicki [16]. They predict that "slow light" property induced by electromagnetically induced transparency (EIT) and coherent population trapping (CPT) may greatly boost the gyroscope's sensitivity by as much as light slows. However, they did not indicate concretely how the gyroscope's sensitivity can be enhanced by slow-light technique. After several years, Shahriar et al. [17,18] proved that this enhancement cannot be achieved for the case of absolute rotation, in which case slow light medium moves together with the rest of gyroscope. They also proved only the case of relative rotation, in which case there is a relative rotation between the slow light medium and the rest of the gyroscope, can enhance the gyroscope's sensitivity. However, the relative rotation between the medium and the rest of the gyroscope, up to now, cannot be used in navigation and aviation. What is needed for these applications is an ability to measure the absolute rotation of the whole gyroscope, including the propagation medium [18]. Therefore, the dispersive medium such as EIT and CPT cannot be utilized to enhance the gyroscope's sensitivity, but the dispersive structure based on photonic crystal or resonator cavities reveals some possibilities. Recently, a series of work aimed to utilized the dispersive structure to enhance gyroscope's sensitivity. Matsko et al. [19,20] proposed a set of coupled whispering gallery mode resonators to realize a high-sensitivity optical gyroscope, but this structure was modeled as a highly-dispersive conventional waveguide where the slow group velocity of the light in this structure stems from the average interaction of the light with the high-Q resonators. Steinberg et al. [21–23] studied the Sagnac effect in rotating coupled photonic crystal defect cavities. Yariv et al. [24] presented a coupled-resonator slow-light waveguide structure to realize highly compact integrated rotation sensors and gyroscopes. Moreover, Peng et al. proposed a two-identical-ring planar structure [25] and a two-identical-ring folded structure [26] which can be employed to construct highly sensitive gyroscopes, respectively.

All these works mentioned above aimed to use slow light to improve the sensitivity of optical gyroscope. In this Letter, we proposed a high dispersive ring-in-ring planar structure which belongs to the dispersive structure, and studied the relationships between the effective Sagnac phase shift and the group index in details.

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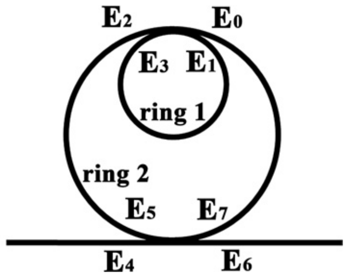

Fig. 1. Illustration of ring-in-ring planar structure.

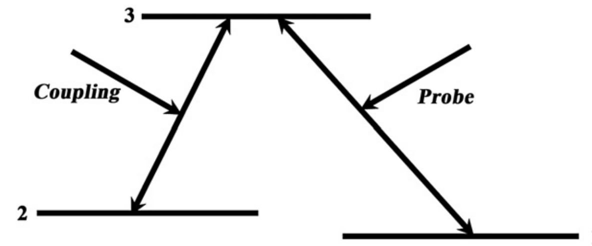

Fig. 2. Schematic illustration of atomic three-level system for the electromagnetically induced transparency.

In addition, we utilize the ring-in-ring planar structure, measuring absolute rotation, to construct a new high sensitive gyroscope.

2. Analysis of ring-in-ring planar structure

The ring-in-ring planar structure is constructed by a waveguide coupled with ring-in-ring resonator, as shown in Fig. 1. It would consume less space than that proposed in Refs. [25,26], where the rings of the former is coupled in tandem to a waveguide, the latter is a folded structure. The radiuses of the two rings in the ring-in-ring resonator, R_1 and R_2, satisfy the relation of $R_2 = 2R_1$. The response of the whole structure can be described by the transmission coefficient, $\tilde{\tau}_2$, which is obtained following the iterative approach [27]:

$$\tilde{\tau}_2(\phi_2, \phi_1) \equiv \frac{\tilde{E}_6}{\tilde{E}_4} = \frac{r_2 - a_2\tilde{\tau}_1 e^{i\phi_2}}{1 - r_2 a_2 \tilde{\tau}_1 e^{i\phi_2}}, \tag{1}$$

where $\tilde{\tau}_1(\phi_1) = (r_1 - a_1 e^{i\phi_1})/(1 - r_1 a_1 e^{i\phi_1})$ is the first ring transmission coefficient, r_j and $t_j = \sqrt{1 - r_j^2}$, $\phi_j = \beta_j L_j$, $a_j = \exp(-\alpha_j L_j/2)$, α_j, L_j, and β_j are the reflection coefficient, transmission coefficient, the phase shift, the attenuation factor, the absorption coefficient, the length, and the propagation constant of the jth ($j = 1, 2$) ring, respectively. According to $\phi_j = \beta_j L_j$, we can be obtained the relation of $\phi_2 = 2\phi_1$. The effective phase shift, $\tilde{\phi}_2^{(\mathrm{eff})}$, for the whole structure is defined as

$$\tilde{\phi}_2^{(\mathrm{eff})}(\phi_2, \phi_1) \equiv \arg(\tilde{\tau}_2). \tag{2}$$

The absorptance of the whole structure is written as [11]

$$\tilde{A}_2(\phi_2, \phi_1) = \frac{\tilde{A}_2^{(\mathrm{env})}}{1 + \tilde{F}_2^2 \sin^2((\tilde{\phi}_1^{(\mathrm{eff})} + \phi_2)/2)}, \tag{3}$$

where $\tilde{A}_2^{(\mathrm{env})}(\phi_1) \equiv (1 - r_2^2)(1 - a_2^2|\tilde{\tau}_1|^2)/(1 - r_2 a_2|\tilde{\tau}_1|)^2$, $\tilde{F}_2(\phi_1) \equiv 4r_2 a_2|\tilde{\tau}_1|/(1 - r_2 a_2|\tilde{\tau}_1|)^2$ is a function related to finesse, $\tilde{\phi}_1^{(\mathrm{eff})}(\phi_1) \equiv \arg(\tilde{\tau}_1)$ is the effective phase shift of the first ring. Under the assumption of $a_1 = 1$, the ϕ_1 dependent term in A_2 can be rewritten as $\sin^2[(\tilde{\phi}_1^{\mathrm{eff}} + \phi_2)/2] = (\cos\phi_1 + 1)(r_1 + 1 - 2\cos\phi_1)^2/2(1 - 2r_1\cos\phi_1 + r_1^2)$. For small detuning $\cos\phi_1 \approx 1 - \phi_1^2/2$, and sufficiently weak coupling between resonators $(1 - r_1)^2 \ll r_1\phi_1^2$, Eq. (3) can be rewritten as:

$$\tilde{A}_2(\delta) = \frac{\tilde{A}_2^{(\mathrm{env})}}{1 + \frac{4(\cos\phi_1+1)}{\gamma^2}[\delta - (\Delta\omega/2)^2/\delta]^2}, \tag{4}$$

where $\gamma = \sqrt{2}(1 - r_2 a_2)/\sqrt{\eta}\tau_R$ is related to the linewidth, τ_R is the first ring round-trip time, $\delta = \phi_1/\tau_R$ is the detuning, $\Delta\omega = 2\sqrt{(1 - r_1)}/\tau_R$ is the frequency difference between the split modes, and $\eta = r_2 a_2/r_1$.

By the way, for an EIT medium with an atomic three-level system illustrated in Fig. 2, when a strong coupling beam is applied, the absorptance of the probe beam can be reduced or even eliminated. The transition rate for absorption of an arbitrarily detuned probe beam is given as [28]

$$W(\Delta) = \frac{[\Omega_p^2/\Gamma]}{1 + \frac{4}{\Gamma^2}[\Delta - (\Omega_c/2)^2/\Delta]^2}, \tag{5}$$

where Ω_p and Ω_c are Rabi frequency of the probe and coupling beam, Δ is the angular frequency detuning of the probe beam, and Γ is the decay rate from level $|3\rangle$ to levels $|1\rangle$ and $|2\rangle$. Comparison of Eq. (4) with Eq. (5), the analogies between CRIT and EIT are $\gamma \to \Gamma, \delta \to \Delta, \Delta\omega \to \Omega_c$ [11].

According to Eq. (4), the curve of the light absorptance ($\tilde{A}_2$) against the phase shift (ϕ_1) of the first ring is shown in Fig. 3(a) for the ring-in-ring planar structure. It is clear that the absorptance of the incident light is obviously reduced or even eliminated at resonance region, i.e., a narrow transparent window appeared at resonance region. The transparent window originates from coherent coupling between rings, analogous to ac-Stark shift and quantum interference that occurs in three level atomic systems. Fig. 3(b) shows a curve of $\tilde{\phi}_2^{(\mathrm{eff})}$ as function of ϕ_1 for the ring-in-ring planar structure based on Eq. (2). From the figure, the steep normal dispersion characteristics of the ring-in-ring planar structure at resonance region is similar to the dispersion in three level atomic systems at zero detuning, i.e., the effective phase shift, $\tilde{\phi}_2^{(\mathrm{eff})}$, can be analogous to the refractive index in three level atomic systems. The strong dispersion results in considerably slow light. As described in Ref. [24], $\tau(\omega) = d\tilde{\phi}_2^{\mathrm{eff}}/d\omega$ is the group delay of the system, $\upsilon_g = L/\tau(\omega)$ is the group velocity, where L is the length of the closed loop, then the group index can be obtained as $n_g = c/\upsilon_g = n_0 d\tilde{\phi}_2^{\mathrm{eff}}/d\phi_1$. Fig. 3(c) shows a curve of $d\tilde{\phi}_2^{\mathrm{eff}}/d\phi_1$ for the ring-in-ring planar structure. It can be easily known slow light occurs and the group velocity reaches the minimum at resonance where the CRIT effect is greatest.

3. Optical gyroscope based on the ring-in-ring planar structure

The ring-in-ring planar structure has high dispersion at resonance, simultaneity, the group velocity reaches minimum with transparent. This structure can be used in absolute rotation sensing to enhance the sensitivity of optical gyroscope. In previous studies, Peng et al. proposed a two-identical planar ring structure [25] and a folded identical ring structure [26] that can be used in optical gyroscope and rotating senor. However, Peng et al. did not devise the specific structure of optical gyroscope, i.e., they did not indicate how counter incident lights propagate in the CRIT structures. In this Letter, we propose a gyroscope structure based on the ring-in-ring planar structure, where the ring-in-ring planar structure is inserted in the loop of an optical Sagnac interferometer. The schematic illustration of the gyroscope structure is shown in Fig. 4. Evidently, the *dispersive structure* (i.e., ring-in-ring planar structure) and the rest of gyroscope are integrated and move together, that is to say, the proposed gyroscope is an absolute rotation sensor. The incident light, in the optical gyroscope, is divided into two coun-