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Fiber ring resonator based slow-light and high sensitivity gas sensing technology

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ABSTRACT

A high sensitivity gas sensing technology based on fiber ring resonator slow-light is proposed and demonstrated in this paper. Slow-light produced by coupled resonator induced transparency in a fiber ring resonator has been studied theoretically and experimentally. Influences of parameters, such as cycle numbers, coupling ratio of couplers, ring loss and coupler additional loss, on slow-light characteristics of the fiber ring resonator were analyzed theoretically and numerically in detail. The delay time of slow-light in the fiber ring resonators has been measured using time domain measuring method, and the maximum delay time of 34.18 ns at wavelength of 1531.63 nm has been obtained, which is in accord with theoretical analysis. The gas absorption coefficient at the wavelength of 1531.63 nm where slow-light generated reached 2.41, which increased by 6.73 times the figure for the traditional method. It is the first time to measure gas concentration by using slow-light in fiber ring resonators, and the method is simple in structure and easy to implement.

1. Introduction

In recent years, researchers have discovered the phenomena of slow-light and fast light in many mediums and structures. There are many ways to slow down the velocity of light and the generation methods can be divided into two categories [1]. One kind is called material slow-light, such as electromagnetically induced transparency [2], coherent population oscillation [3], stimulated Brillouin scattering [4], stimulated Raman scattering [5] and photorefractive effect [6], etc. The other kind is called structural slow-light, such as fiber Bragg grating [7], photonic crystals [8], coupled resonator cavity [9], etc. High quality experimental equipments and environment are required to control slow-light based on dispersion medium, so it is difficult to achieve. As for slow-light based on dispersion structure like fiber ring resonator, wavelength that slow-light generated can be easily adjusted by changing structure parameters (such as ring numbers, coupling ratio of the two couplers), and what's more, it is easy to implement.

In 1990, Harris [10] proposed the electromagnetically induced transparency (EIT) technology to slow down the velocity of light and the light absorption is weak. In 1999, Hau [11] slowed velocity of light pulses in sodium atomic vapor successfully down to 38 miles per hour by using EIT technology. In recent years, some literatures show by using two coupled resonators, the effect which is similar to the EIT effect can be produced, and this effect is called CRIT effect [12,13]. The two coupled resonator manufactures division of resonant frequency, which is similar to the Rabi division of EIT effect, and the division can offset the inevitable absorption of light for the single resonator, so that it is feasible to produce slow-light by using the effect of CRIT. In 2004, Smith [12] proposed a CRIT structure. In the same year, he discussed the different results between CRIT and coupled resonator induced absorption (CRIA), when the reflection coefficient of coupler and the loss of the ring respectively meet overcoupling and undercoupling. And he analyzed whether slow or fast light produced in the case of different coupling coefficient of the structure, and then carried out simulations on the coupling resonance structure with a two-level system. In 2006, Smith [14] has realized CRIT effect by utilizing optical fiber system. The paper studied slow-light phenomenon in the optical fiber coupled structure by using finite difference time domain method and the CRIT phenomenon was observed in the system. Mode split is observed in the transmission spectrum because of the constructive interference in the resonance point, and there is a transparent window in the resonance frequency. The phenomenon of delay time of 6.2 ns slow-light is observed in the experiment [15]. In 2008, Dumeige [16] studied CRIT phenomenon in erbium-doped

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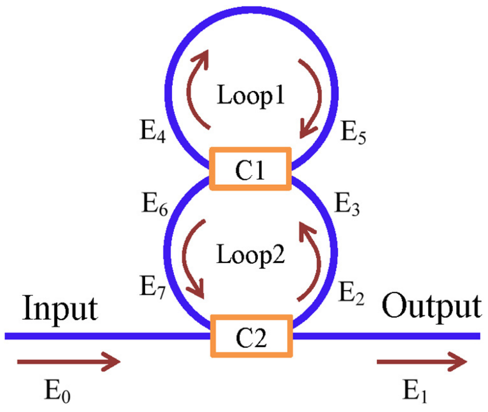

Fig. 1. Fiber ring resonator based on the CRIT effect.

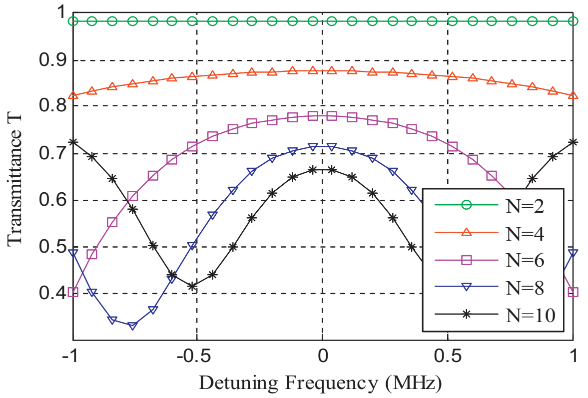

Fig. 2. Transmittance for different ring number *N*.

fiber, and the slow-light signal was measured by the method of interference.

This paper studied theory for producing slow-light in optical fiber ring resonator based on CRIT effect, and the factors that affect slow-light characteristics of fiber ring resonator are analyzed. For the first time, this paper proposed and demonstrated a high sensitivity gas sensing method based on slow-light produced by fiber ring resonator to enhance gas absorption coefficient. Compared with photonic crystal waveguide slow-light, this method possesses the advantage of simple structure, good compatibility with fiber optic systems, low cost and it is easy to implement.

2. Theory and numerical analysis

Fiber ring resonator based on CRIT is illustrated in Fig. 1. The length of fiber optic rings are both L, while light traveling through a coupler, compared to the incident light, the light phase of straight arm and the input light is same, but the phase shift between coupling arm and input light is $\pi/2$.

The variation of the phase shift that light traveling a circle through a ring is shown in Eq. (1).

$$\varphi = \frac{2\pi nL}{\lambda} = \frac{\omega nL}{c} \tag{1}$$

where L, n, λ and ω are the length of fiber ring, refractive index of the structure, the wavelength and frequency input light respectively. The transmission function of the first ring is shown in Eq. (2).

$$\tau_1 = \frac{E_6}{E_3} = \frac{r_1 a_{\gamma_1} - a_1 a_{\gamma_1}^2 \exp(i\varphi_1)}{1 - r_1 a_1 a_{\gamma_1} \exp(i\varphi_1)} = |\tau_1| \exp(i\varphi_1^{\mathrm{eff}}) \tag{2}$$

The transmission function of the second ring is shown in Eq. (3).

$$\tau_2 = \frac{E_1}{E_0} = \frac{r_2 a_{\gamma_2} - a_2 a_{\gamma_2}^2 \tau_1 \exp(i\varphi_2)}{1 - r_2 a_2 a_{\gamma_2} \tau_1 \exp(i\varphi_2)} = |\tau_2| \exp(i\varphi_2^{\mathrm{eff}}) \tag{3}$$

where r_j, a_j are reflection coefficient of coupler and loss of the loop respectively. And $a_{\gamma 1}$, $a_{\gamma 2}$ are the additional loss coefficient of loop1 and loop2 respectively. The power transmission coefficient can be written as Eq. (4).

$$T_2 = \frac{|E_1|^2}{|E_0|^2} = |\tau_2|^2 \tag{4}$$

The effective phase shift of the structure is shown in Eq. (5).

$$\varphi_2^{\mathrm{eff}} = arg(\tau_2) \tag{5}$$

The dispersion characteristics of the structure can be obtained by deriving effective phase shift respected to φ_2. Near the resonance point, According to Kramers–Kronig relations, variable rate of strong effective refractive index near the resonance point can be considered as the effective refractive index of high dispersion, linked with CRIT effects represented by Eq. (6).

$$n'(\omega) + \omega \frac{\mathrm{d}n'(\omega)}{\mathrm{d}\omega} = n \frac{\mathrm{d}\varphi_2^{\mathrm{eff}}}{\mathrm{d}\varphi_2} \tag{6}$$

The expression for fiber ring resonator group refractive index is shown in Eq. (7).

$$n_g = n_0 \frac{\mathrm{d}\varphi_2^{\mathrm{eff}}}{\mathrm{d}\varphi_2} \tag{7}$$

The resulting expression for fiber ring resonator group delay is shown in Eq. (8).

$$t_g = \frac{Ln}{c} \frac{\mathrm{d}\varphi_2^{\mathrm{eff}}}{\mathrm{d}\varphi_2} \tag{8}$$

According to the above analysis, the transmission function of N rings is shown in Eq. (9).

$$\tau_N = \frac{r_N - a_N \tau_{N-1} \exp(i\varphi_N)}{1 - r_N a_N \tau_{N-1} \exp(i\varphi_N)} = |\tau_N| \exp(i\varphi_N^{\mathrm{eff}}) \tag{9}$$

While the cycle number is odd, simulation and analysis on the structure transmittance, effective phase shift, group of refractive index and group delay show that there is CRIA phenomenon around the resonance point. The negative change rate of effective phase shift can be considered as anomalous dispersion, namely when group index and group delay of the system is negative, fast light will be produced in this structure. When the cycle number is even, there is CRIT phenomenon around the resonance point, which is a very narrow transparent peak, and the positive change rate of effective phase shift can be considered as normal dispersion, namely when group index and group delay of the system is positive, slow-light will be produced in this structure.

Fig. 2 shows the transmittance versus cycle number *N*, and it shows that the transmittance and line width decreases gradually when the cycle number increases. The effective phase shift to even cycle number *N* is shown in Fig. 3, and it shows the change rate of effective phase shift also refractive index and the group delay increase gradually when the cycle number increases.

Fig. 4 shows the transmission spectrum for different coupling ratio of C1. As it can been seen, as coupling ratio of C1changing from 10:90 to 90:10, the transmissivity at the resonant point is almost the same and the line width decreases rapidly.

The relations between group delay and coupling ratio of coupler C1 is shown in Fig. 5. Along with group delay increases, the line width and the frequency range of producing slow-light gradually decreases accordingly. Considering the influence of coupling ratio