Slow light Mach-Zehnder fiber interferometer

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A slow light structure Mach-Zehnder fiber interferometer is theoretically demonstrated. The sensitivity of the interferometer is significantly enhanced by the dispersion of the slow light structure. The numerical results show that the sensitivity enhancement factor varies with the coupling coefficient and reaches its maximum under critical coupling conditions.

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Interferometers have been investigated in relation to their applications in fields such as metrology[1], optical sensing[2], optical communication[3,4], quantum information processing[5], and biomedical engineering[6]. A number of schemes have been proposed to improve the performance of interferometers[7], such as using photonic crystal structures to minimize the size of on-chip devices[8], utilizing the dispersive property of semiconductor to enhance the spectral sensitivity of interferometers[9,10], utilizing slow light medium to enhance the resolution of Fourier transform interferometer[11], exploiting fast light medium or slow light structure to increase the rotation sensitivity of a Sagnac interferometer[12,13], enhancing the transmittance of the Mach-Zehnder interferometer (MZI) in the slow light region by gratings[14], and using liquid crystal light valve to derive high sensitivity interferometers[15].

Most of the slow light interferometers mentioned above use slow light media to enhance the sensitivity of the interferometer. However, all optical fiber interferometers are widely used in sensing systems because of their simplicity, compactness, and stability. This necessitates the enhancement of the sensitivity of fiber interferometer, which has become a pressing task. Coupled resonator structures can also display slow and fast light performances[15−21] and can connect easily to the fiber systems. For these reasons, an approach is proposed to enhance the sensitivity of an optical Mach-Zehnder (M-Z) fiber interferometer by introducing a slow light structure. The slow light structure can considerably increase the sensitivity of a M-Z fiber interferometer.

Figure 1 illustrates a single fiber ring resonator, which consists of a fiber ring and a fiber coupled with a resonator. Optical resonators can be analogous to the atomic resonances in slow light research. The effective phase shift φ^{eff} imparted to the light transmitted across a structure is analogous to the polarizability of an atom. Therefore, such structures can be analogous to optical media, and as such, the contribution to the group index from an optical ring resonator is proportional to $\mathrm{d}\varphi^{\mathrm{eff}}/\mathrm{d}\phi$[18]. The effective phase shift of the ring shown in Fig. 1 is given by

$$\varphi^{\mathrm{eff}}(\phi) = \pi + \phi + \arg\left(\frac{a - r\mathrm{e}^{-\mathrm{i}\phi}}{1 - ra\mathrm{e}^{-\mathrm{i}\phi}}\right), \quad (1)$$

where r is the reflection coefficient, a is the attenuation factor of the fiber, and ϕ is the single-pass phase shift of the ring. $\mathrm{d}\varphi^{\mathrm{eff}}/\mathrm{d}\phi > 0$ and $\mathrm{d}\varphi^{\mathrm{eff}}/\mathrm{d}\phi < 0$ correspond to normal and anomalous dispersions, respectively. The group delay of the dispersions can be defined by the radian-frequency derivation of the effective phase shift, which can be expressed as

$$t_{\mathrm{d}} \equiv \left.\frac{\mathrm{d}\phi^{\mathrm{eff}}(\omega)}{\mathrm{d}\omega}\right|_{\omega=\omega_0}. \quad (2)$$

The radian-frequency ω is related to the round-trip phase shift according to $\phi = \omega t$, where t is the round-trip time of the resonator, and $t_{\mathrm{d}} > 0$ and $t_{\mathrm{d}} < 0$ refer to slow and fast lights, respectively. Experimental results on slow light with fiber ring resonators have been reported in recent years[22].

Figure 2 shows the sketch of a fiber interferometer coupled with a slow light structure.

A single-fiber ring resonator is coupled within the sensing arm of the MZI. The dashed square frame marks the sensing unit. The lengths of the two arms are made equal. The optical path difference between the upper and lower arms through the MZI is caused only by the ring resonator.

As mentioned in Ref. [9], the sensitivity of a slow light MZI can be described typically in terms of the quantity $\mathrm{d}\Delta\Phi/\mathrm{d}\omega$.

$$S = \frac{\mathrm{d}\Delta\Phi}{\mathrm{d}\omega} = \frac{L}{c} n_{\mathrm{g}}, \quad (3)$$

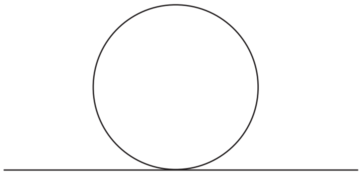

Fig. 1. Sketch of a single fiber ring resonator.

where L is the length of the slow light structure and $n_{\rm g}$ is the group index. For traditional fiber interferometers in which non-dispersive structure is used, $n_{\rm g}$ equals the phase index of fiber. Therefore, the dependence of sensitivity on dispersion can be neglected. However, if a slow-light structure is used with a very large group index $n_{\rm g}$, the sensitivity of the interferometer can be enhanced significantly.

The sensitivity of a ring resonator coupled fiber interferometer can be given by

$$S=\frac{{\rm d}\Delta\Phi}{{\rm d}\omega}=\frac{{\rm d}\varphi^{\rm eff}}{{\rm d}\phi}\frac{{\rm d}\phi}{{\rm d}\omega}=\frac{nL}{c}\frac{{\rm d}\varphi^{\rm eff}}{{\rm d}\phi}=\frac{L}{c}n_{\rm g},\qquad(4)$$

where $\Delta\Phi$ is the phase difference of the two arms, which is equal to the effective phase shift of the fiber ring resonator in the system as illustrated in Fig. 2, and ϕ is the single-pass phase shift of the ring coupled to the fiber interferometer. We define the dispersion sensitivity as $S'={\rm d}\varphi^{\rm eff}/{\rm d}\phi=n_{\rm g}/n$. The sensitivity of the interferometer is proportional to the dispersion sensitivity S'. This means that the sensitivity of the interferometer can be enhanced while the dispersion sensitivity S' can be increased.

In Fig. 3, the effective phase shift $\varphi^{\rm eff}$ undergoes a rapid shift at a resonance corresponding to anomalous dispersion. This leads to the large value of ${\rm d}\varphi^{\rm eff}/{\rm d}\phi$ at the resonance. Thus, the sensitivity of MZI will be enhanced by the coupled fiber ring resonator.

The dispersion sensitivity S' of the two ring coupled MZI is illustrated in Fig. 4. The sensitivities are clearly enhanced around the resonant region when the fiber rings are coupled to the MZI. The maximum sensitivity value of the ring coupled MZI appears at the resonance of the fiber ring resonator, and the dispersion sensitivity S' of the traditional MZI is constant.

The enhancement factor of the sensitivity of the fiber ring coupled MZI in relation to that of the traditional interferometer can be defined by

$$\zeta=\frac{S}{S_t}=\frac{n_{\rm g}}{n},\qquad(5)$$

where ζ >1 indicates the enhancement of the sensitivity.

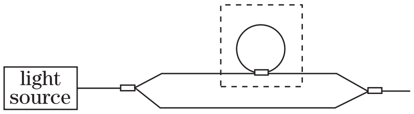

Fig. 2. MZI coupled with a single fiber ring resonator (SFRR).

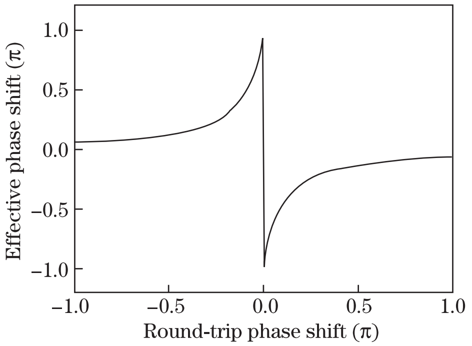

Fig. 3. Effective phase shift versus round-trip phase shift.

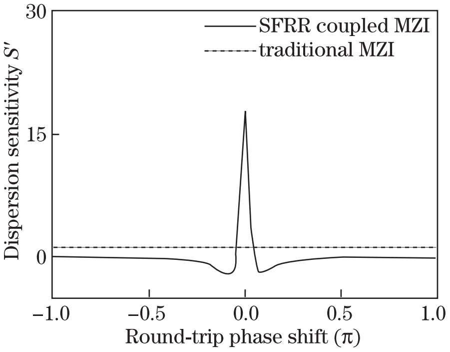

Fig. 4. Dispersion sensitivity S' of the SFRR coupled MZI and dispersion sensitivity S' of the traditional MZI. The solid line represents the SFRR coupled MZI, and the dotted line denotes the traditional interferometer.

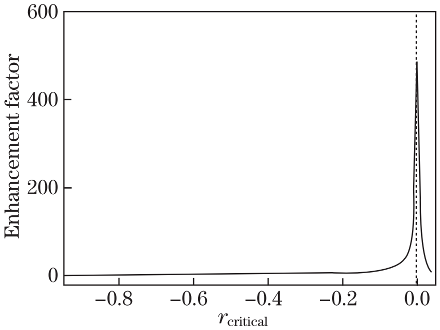

Fig. 5. Enhancement factor of the sensitivity of the SFRR coupled MZI compared with the traditional MZI ($r_{\rm critical}$ is the reflection coefficient at critical coupling).

The enhancement factor of the sensitivity of the fiber ring coupled MZI compared with that of the traditional interferometer is demonstrated in Fig. 5. It is assumed that the other structure parameters are constant. The enhancement factor of the fiber ring coupled MZI is extremely large when the coupling coefficient is near the critical coupling coefficient. The coupling coefficient reaches its maximum value under critical coupling and decreases with the coupling coefficient leaving from the critical coupling.

In conclusion, a modified MZI based on the slow structures is proposed. The significant increase of sensitivity of the modified MZI around the resonant region of the fiber ring, and the capability to obtain the maximum value at resonance are theoretically confirmed. The enhancement factor varies with the coupling coefficient and reaches its maximum under critical coupling conditions.

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