Optical bistability in tunable fiber laser using fiber Mach-Zehnder interferometer

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In this letter, a novel mechanism of hybrid optical bistability is proposed by using nonlinear mechanism in the frequency domain. This device is based on electro-optical feedback through the fiber Bragg grating on piezoelectric transducer (PZT) to tune continuous wave (CW) fiber laser. The optical bistable characteristics for two manners of separately alternating input power and bias voltage are discussed. The smallest wavelength shift of the order of 0.001 nm needed to realize a switching process in this optical bistability device is estimated. The potential applications of this device in the optical fiber sensor technique are also discussed.

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In recent years, intensive research on optical fiber bistable devices (OBDs) has been carried out[1−11]. OBD has many important applications in optical fiber communications, fiber optic sensors, and optical signal processing, etc.. Generally optical bistability can be caused by nonlinear absorption or some other nonlinear effects. There are two classes of OBDs, the intrinsic and hybrid OBDs. It is well known that a hybrid bistable device can be constructed with an optical filter in which an appropriate nonlinearity in the filter transmission is combined with a certain feedback mechanism[1]. Optical filters are the key components in optical fiber communication technique, in which Mach-Zehnder interferometer (MZI) is one of the potential candidates because of its inherently lower loss, spectral selectivity, and lower cost. The transmission spectrum of a fiber MZI is characterized by a series of equally spaced peaks in the frequency domain. It meets the requirement for nonlinear transmission function to exhibit optical bistability because of possessing extreme points and inflection points[1]. So far, several hybrid OBDs which employ MZI as the modulator have been reported[8,9]. In all these OBDs the nonlinear transmission curves are obtained by changing the optical path of MZI.

In this letter, we propose a novel mechanism of hybrid optical bistability using nonlinear mechanism in the frequency domain. In this OBD, MZI is also employed as the modulator, however the nonlinear transmission curve is obtained not by changing the optical path, but through changing the wavelength of the light source. This device is based on electro-optical feedback through the fiber Bragg grating on piezoelectric transducer (PZT) to tune continuous wave (CW) fiber laser. The schematic diagram of the OBD is shown in Fig. 1. In our experiment, the source is a tunable laser with FBG, because it has the advantages of compactness in fiber design, selectivity of accurate wavelength, and larger tuning range through the strain on PZT. The light from the tunable fiber laser is launched into fiber MZI. The electro-optical feedback elements include the photo detector and the electric amplifier.

The condition of Bragg reflection is $\lambda_{\mathrm{B}} = 2n_{\mathrm{FBG}}\Lambda$, where λ_{B}, n_{FBG}, and Λ are the central wavelength, effective refractive index, and period of FBG, respectively. Any change in n_{FBG} or Λ results in a shift of FBG central wavelength. The output wavelength of the fiber laser can be tuned by adjusting the voltage on PZT that causes an axial strain on FBG. When the voltage on PZT increases, the laser wavelength shifts towards a longer side. In our experiment, the curve of fiber laser wavelength versus the voltage on PZT can be fitted with

$$\lambda = 1547.852 + 0.00423 \times V. \tag{1}$$

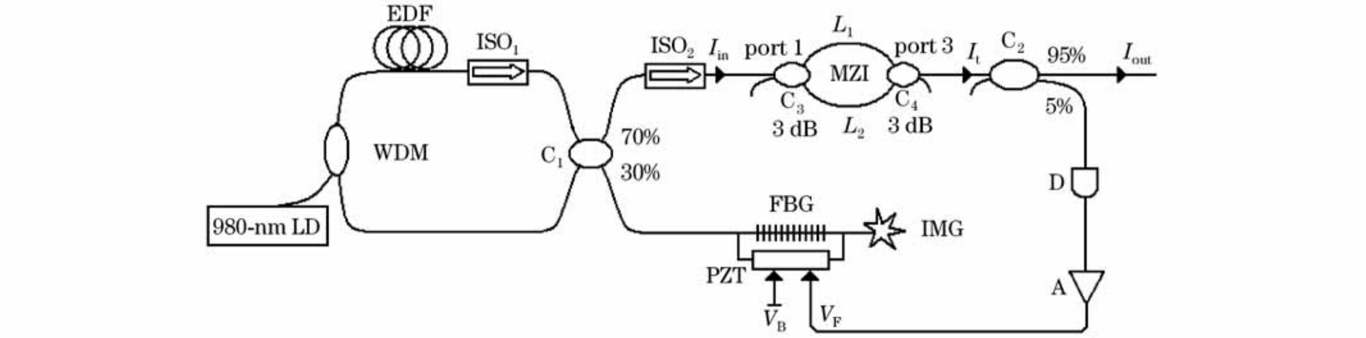

Fig. 1. The experimental setup. $\mathrm{C}_1 - \mathrm{C}_4$: couplers; D: photo detector; A: electric amplifier; ISO_1 and ISO_2: isolators; EDF: erbium-doped fiber; WDM: wavelength division multiplexer; LD: laser diode; IMG: index matching.

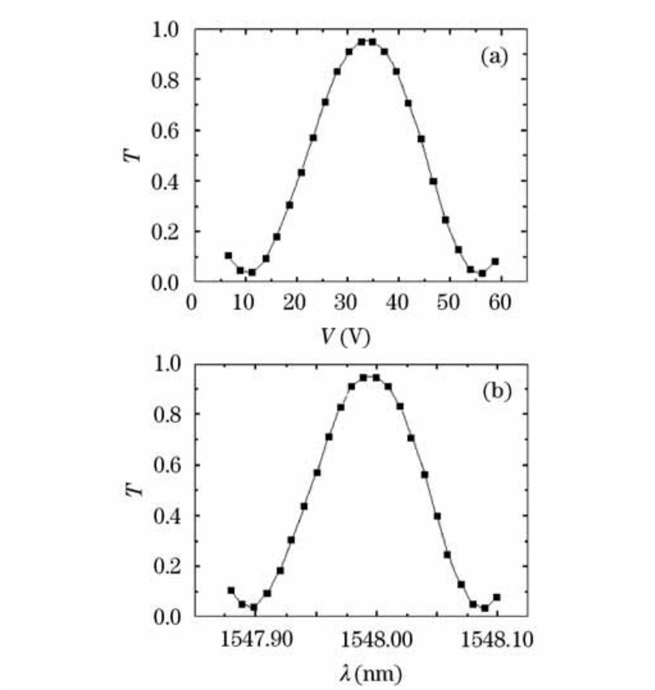

Fig. 2. The relations of transmittivity with tuning voltage (a) and wavelength (b).

From Eq. (1), we can see that, the central wavelength of the fiber laser will shift 0.001 nm when V changes 0.236 V. It can be easily accomplished in experiment.

The output light from fiber laser with intensity $I_{\rm in}$, scanning in wavelength, is transmitted through an isolator which functions as a bandpass filter to MZI with intensity I_t. The transmission characteristics, namely the transmittivity $T_{\rm out}$ versus tuning voltage V is measured and shown in Fig. 2. From Fig. 2 we can find that the fitting curves have pretty cosine distribution.

In general, the geometrical lengths of the two interferometer arms are not equal. There is a path difference $\Delta L = L_1 - L_2$, which is one of the important parameters for the spectral response of the MZI. The wavelength spacing $\Delta\lambda$ between the transmission peaks can be given by $\Delta\lambda = \lambda^2/n_{\rm MZ}\Delta L$, where $n_{\rm MZ}$ is the effective refractive index of the fiber core of MZI. The MZI should be put into a thermostat to keep the ΔL constant. For the port1 input case, the intensity transmitted from port3 is written as

$$I_{\rm t} = \frac{1}{2} I_{\rm in}\alpha(1 + M\cos\Delta\phi), \tag{2}$$

with

$$\Delta\phi = (2\pi n_{\rm MZ}\Delta L)/\lambda, \tag{3}$$

where α is a constant depending on the insertion loss, M is the visibility defined as $M = 2\sqrt{I_{\max} I_{\min}}/(I_{\max} + I_{\min})$, $\Delta\phi$ is the phase difference between two arms of MZI.

In our experiment, $V_{\rm B}$ is the bias voltage and $V_{\rm F}$ is the feedback voltage applied on PZT through a feedback circuit constituted by the photo detector and electric amplifier, and proportional to $I_{\rm t}$. We have

$$T(V) = \frac{I_{\rm t}}{I_{\rm in}} = \frac{1}{\eta K_2 G I_{\rm in}}(V - V_{\rm B}), \tag{4}$$

and

$$V = V_{\rm F} + V_{\rm B} = \eta K_2 G I_{\rm t} + V_{\rm B}, \tag{5}$$

with

$$I_{\rm out} = (1 - K_2) I_{\rm t}, \tag{6}$$

where η, K_2, and G are the conversion efficiency of photo detector, coupling ratio of coupler C_2, and the gain of electric amplifier, respectively. We fixed $\eta = 0.54$ V/mW, $K_2 = 5\%$ in the later simulation. Operation points of the OBD are determined by the solutions of Eqs. (2) and (4), it can be directly expressed in terms of intersections between series of feedback lines and the transmissivity curve. Normally, there are two operation manners to realize bistable behaviors separately: keeping $I_{\rm in}$ constant and adjusting $V_{\rm B}$ gradually or *vice versa*.

In the first operation manner, seeing Fig. 3(a), $V_{\rm B}$ and G are fixed. When $I_{\rm in}$ increases first and then decreases, correspondingly, the feedback curves moves along the direction 1→2→3 first and then back along 3→2→1. In this process, the operating point moves along a → b → d → e, and then moves along e → d → c → a, forming a hysteresis curve as shown in Fig. 4(a).

We have simulated the characteristics of OBD by alternating the feedback curve slope. The simulation result is shown in Fig. 5(a). It can be seen that the result agrees well with the experimental curves in Fig. 4(a).

Figure 3(b) shows the second operation process, $I_{\rm in}$ and G are kept constant. While $V_{\rm B}$ increases first and then decreases, the feedback lines will move parallelly. The corresponding hysteresis curve is shown in Fig. 4(b). Figure 5(b) illustrates the calculated results from Eqs. (2), (4), (5), and (6). This manner can be used as optical bistable sensor with high accuracy. In this manner, the output of OBD can be converted to electrical pulse signal.

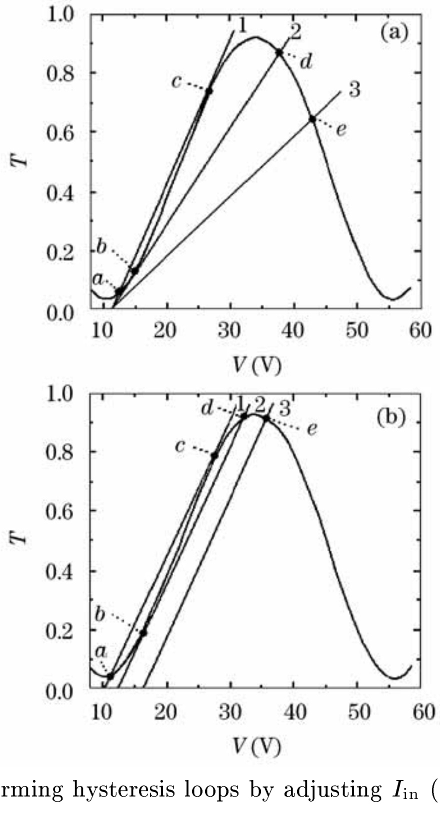

Fig. 3. Forming hysteresis loops by adjusting $I_{\rm in}$ (a) and $V_{\rm B}$ (b).

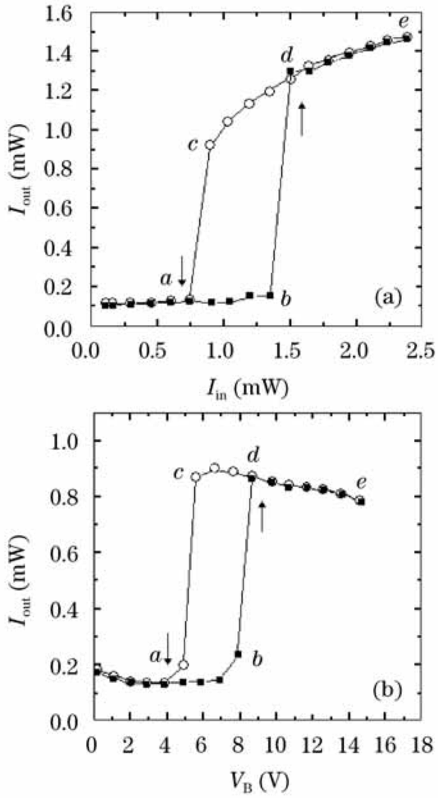

Fig. 4. The experimental hysteresis loops by adjusting $I_{\rm in}$ (a) and $V_{\rm B}$ (b).

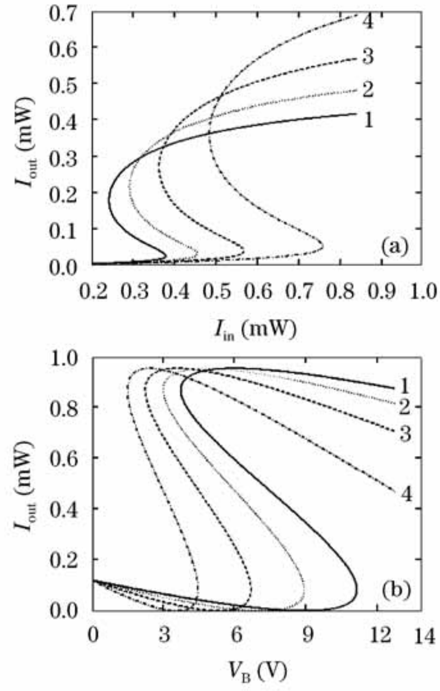

Fig. 5. Simulations of S-shape curves of OBD. (a) Alternating $I_{\rm in}$ with different G, where curves $1-4$ correspond to $G =$ 3000, 2500, 2000, and 1500, respectively; (b) alternating $V_{\rm B}$ with different $\eta K_2 G$ and $I_{\rm in}$ =1 mW, curves $1-4$ correspond to $\eta K_2 G$ = 27, 21.6, 16.2, and 10.8, respectively.

From Fig. 5(a) we can see that the width of the hysteresis loop become narrower when increasing the gain of the amplifier for the first operation manner. While increasing the slope of the feedback line can reduce the width of the OBD loop, which is reversely proportional to $\eta K_2 G I_{\rm in}$ (see Fig. 5(b)). The width of the hysteresis can be calculated from Eqs. (2), (4), (5), and (6). When the value of G tends to 1, the width of the hysteresis is approaching to zero. In practical terms, to realize switching process stably, we choose the gain of the electric amplifier G = 32, the width of the hysteresis loop will be 0.236 V, namely the bias voltage $V_{\rm B}$ changes 0.236 V, and the OBD will switch on or off. We can calculate the wavelength changes of the tunable laser by Eq. (1), which is about 0.001 nm. The switching time of this OBD is determined by the dominant factor performance of the PZT, about several milliseconds.

In our experiment, optical bistable loop can be obtained by adjusting $V_{\rm B}$, correspondingly by changing the laser wavelength. The minimum value of hysteresis loop width is estimated as of the order of 0.001 nm. It means that when the output laser wavelength changes about 0.001 nm, the OBD exhibits a switching process. When the measurand such as strain or temperature causes a shift of the wavelength for transmitted peak by amount of the order of 0.001 nm (equivalent to shifting the feedback line by the same amount), the OBD will switch up or down as described above. This process may be used to monitor the change in strain or temperature causing the wavelength shift of the fiber laser in the digital way. The result of this experiment can also be used in fiber laser stabilizer, which may find applications in fiber communication and fiber sensing, because the upper state is stable in the large input range.

In conclusion, we have demonstrated the hybrid optical bistability by tunable fiber laser with feedback mechanics scanning fiber MZI. It is believed that this device will be very useful in fiber technology with its advantage of ease to be connected with other fiber communication elements.

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