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RESEARCH ARTICLE

Magnetic tunability of fiber optical parametric oscillators with optical clock extraction

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Abstract A 10 Gb/s all-optical clock extraction based on magnetically controllable fiber optical parametric oscillator (MC-FOPO) is demonstrated. The operation properties of the magnetic control unit, composed of a solenoid and a magneto-optic crystal of high Verdet constant, are experimentally investigated. By adjusting the drive current of the solenoid, the magneto-optic crystal unit may serve as a tunable optical fiber delay line with polarization control to some extent. The experimental results show that the MC-FOPO is capable of repetitively magnetic tunability desirable for all-optical clock recovery.

Keywords fiber optical parametric oscillator (FOPO), clock extraction, magnetic control

1 Introduction

Optical clock recovery (OCR) is one of the key technologies for 3R (re-timing, re-shaping and re-amplification) regeneration in all-optical communications. Fiber optical parametric oscillators (FOPOs) can not only be used to realize OCR, but also have some unique advantages over other OCR schemes (such as clock recovery based on Fabry-Perot filter) in high speed response, high data rate, broad wavelength tunability, etc. [1]. However, the stability of FOPOs which has a direct impact on the quality of the extracted clock still need to be improved further. The main reason for the instability is the drift of the cavity caused by environmental factors. At present, there are three often-used methods to stabilize the cavity of the FOPOs as follows:

1) Using dispersion-shifted fiber (DSF) [2]

When a pulsed pump is launched into a cavity with a DSF, parametric fluorescence will be amplified and feed back to fiber input as a seed. The relationship between fiber length (L) and dispersion (D) is expressed as

$$\Delta\tau = DL\Delta\lambda,$$

where $\Delta\tau$ is the time delay difference corresponding to the wavelength change $\Delta\lambda$. Thus, it may compensate for the length variation of fiber loop cavity by tuning the wavelength of the output clock signal to match up to the input data rate.

2) Mode-locking method [3]

The active mode-locking method is demonstrated to lock the phases of multiple longitudinal modes. The round-trip time for a pulse inside the cavity of the FOPOs depending on the wavelength and a large dispersion of the cavity will help to synchronize the pulse with external modulation frequency automatically. The FOPOs can be simply tuned by adjusting the external modulation frequency and it can generate two pulse trains at the signal and the idler wavelengths. By utilizing an automatic scanning frequency from an external clock, it has a potential to be developed as a fast sweeping pulsed source. The output clock is stabilized by changing repetition rate. But this approach not only adds an external clock, but also changes the repetition rate.

3) Inserting an optical delay line (ODL) to the cavity [4]

The ODL provides a time delay for the optical signal and is used to adjust the cavity length in order to compensate for the drift of cavity length. But low sensitivity and long lag time lead to a bad extracted clock.

In this study, we insert a magneto-optic crystal into the fiber loop cavity of FOPOs and find that the variation of the extracted clock with the external magnetic field has a good repetition and reversibility, that is, the extracted clock can be improved by tuning the external magnetic field. On the other hand, the magnetic control method not only acts as an ODL in compensating for the drift of cavity length to some degree, but has some unique advantages of low cost, high precision, non-mechanical control, quick response, etc.

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2 Magnetic control methods for FOPOs

There are two magnetic control schemes to be used in FOPOs. One is a centralized magnetic control method [5,6] using a magneto-optic crystal and a solenoid as shown in Fig. 1(a). The magnetic field is generated by a solenoid under control of its current. The other is a distributed magnetic control method, and highly nonlinear fiber (HNLF) is magnetized by a toroid coil, as shown in Fig. 1(b). Table 1 lists some parameters of the solenoid and the toroid coil used in our laboratory. In this paper, we focus on the first scheme (Fig. 1(a)), in which a magneto-optic crystal is inserted into the cavity as a control component to compensate for the drift of cavity length induced by environmental temperature.

2.1 Magneto-optic (MO) crystal unit

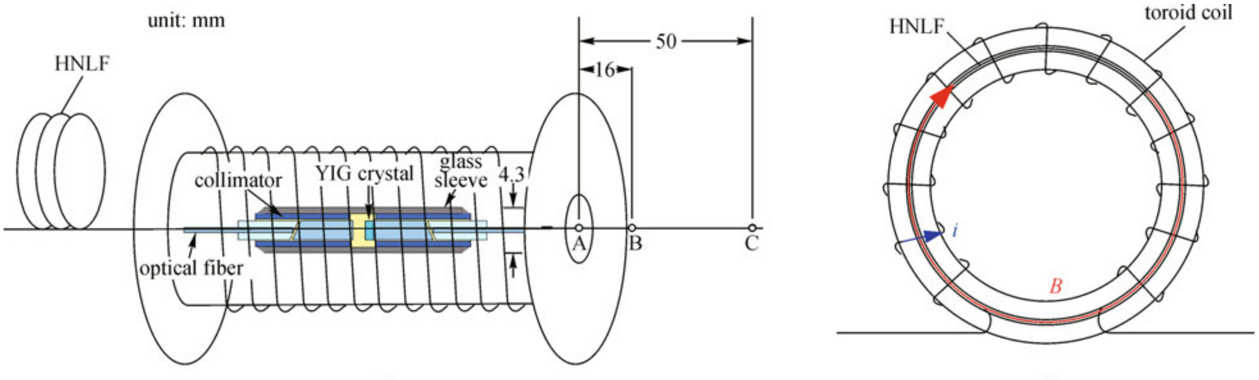
We use a customized magneto-optic crystal unit as a magnetic control component in the cavity to compensate for the drift of cavity length. The unit consists of a couple of collimators, yttrium iron garnet (YIG) crystal, and glass sleeve, as shown in Fig. 1(a). The refractive index of the YIG crystal is 2.3–2.4, and the working temperature is 5°C–70°C.

For the magneto-optic crystal, the Faraday rotation angle $\theta = V_B B l$, where V_B is the Verdet constant of the magneto-optic crystal, B is the magnetic flux density in the propagation direction, and l is the length of the magneto-optic crystal. Figures 2(a) and 2(b) show the magnetic field dependences of the insertion loss, the Faraday rotation angle and the Verdet constant for the 0.43 mm-long magneto-optic crystal. Their saturation properties occur at about 160 Gs and the Verdet constant also depends on the magnetic field.

2.2 Magnetic field distribution of solenoid

The magnetic field distribution on the solenoid axis can be given by [7]

$$B = \frac{1}{2}\mu_0 n I \left\{ \left(\frac{L}{2}+z\right)\ln\frac{r_0+\sqrt{r_0^2+\left(\frac{L}{2}+z\right)^2}}{r_{\mathrm{i}}+\sqrt{r_{\mathrm{i}}^2+\left(\frac{L}{2}+z\right)^2}} + \left(\frac{L}{2}-z\right)\ln\frac{r_0+\sqrt{r_0^2+\left(\frac{L}{2}-z\right)^2}}{r_{\mathrm{i}}+\sqrt{r_{\mathrm{i}}^2+\left(\frac{L}{2}-z\right)^2}} \right\}, \quad (1)$$

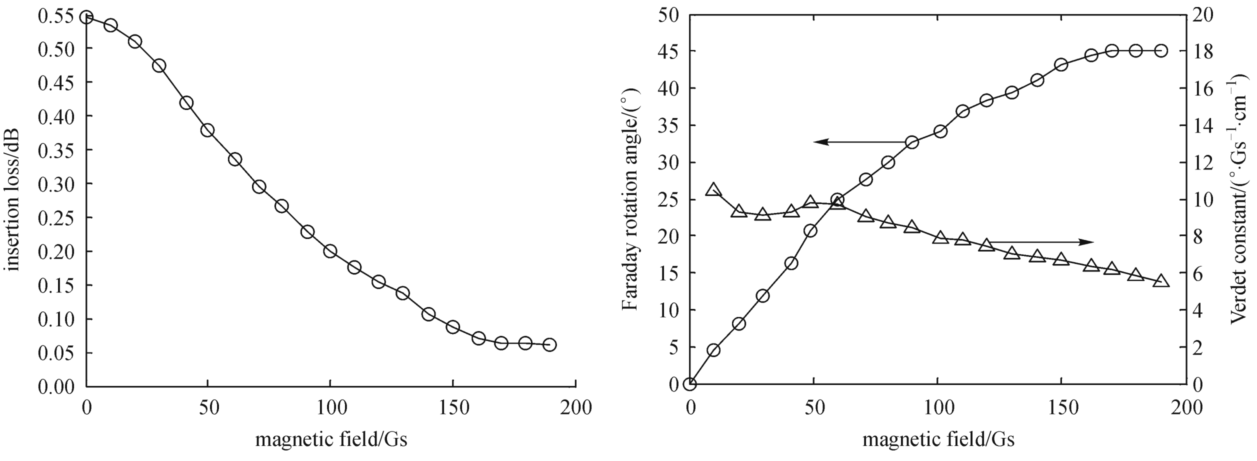


(a) (b)

Fig. 1 Magnetic control methods used in fiber optical parametric oscillators. (a) Centralized magnetic control; (b) distributed magnetic control

Table 1 Some parameters of solenoid and toroid coil

parameters	solenoid	toroid coil
internal diameter	30 mm	86 mm
external diameter	80 mm	100 mm
size	80 mm×80 mm×100 mm	170 mm×170 mm×100 mm
maximum current	2.5 A	15 A
cost	500 RMB	8000 RMB
maximum magnetic field	> 300 Gs	180 Gs
temperature sensitivity	low	high
uniform region	15 mm at the center	any position on the axis
applications	magneto-optic crystals	fibers



(a)

(b)

Fig. 2 Magnetic field response of magneto-optic crystal. (a) Insertion loss; (b) Faraday rotation angle and Verdet constant

where z is the distance from the central point of the solenoid, n is the multilayer coil density in the sectional view, r_i and r_0 are, respectively, the internal and external radii of the solenoid with the length $L = 100\,\text{mm}$. The parameters in Eq. (1), n, r_i and r_0, may be determined from the magnetic fields at the points A, B (1.6 cm from A) and C (5 cm from A) along the axis of the solenoid (as shown in Fig. 3) and we have $n = 6.764\,\text{mm}^{-2}$, $r_0 = 39.6\,\text{mm}$, and $r_\text{i} = 18.8\,\text{mm}$. And the magnetic field distribution inside the solenoid can be calculated from Eq. (1), as shown in Fig. 4. The origin point of abscissa axis corresponds to the center of the solenoid and the uniform region is longer than 15 mm. Clearly, the magnitude of magnetic field is proportional to the driver current of the solenoid.

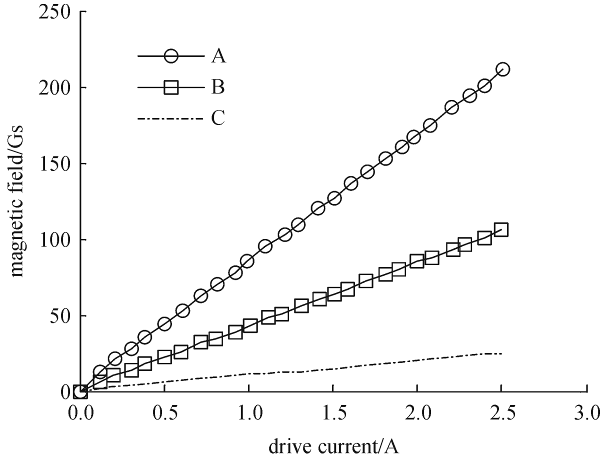


Fig. 3 Relation between magnitude of magnetic field and drive current

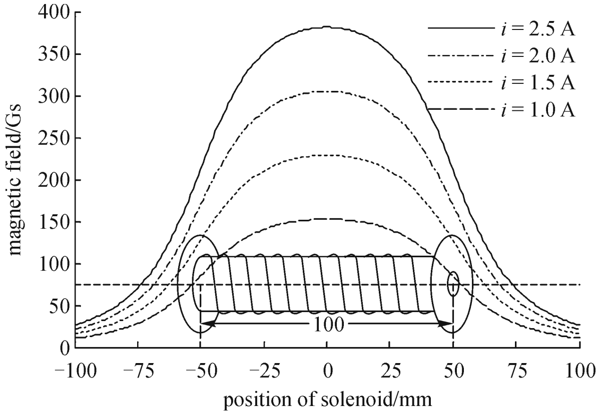


Fig. 4 Magnetic field distribution of solenoid

3 Experimental setup of magnetically controllable fiber optical parametric oscillators (MC-FOPOs)

The magnetically controllable FOPO (MC-FOPO) based on parametric gain is mainly composed of an active fiber loop, a magneto-optic crystal, and a solenoid. The detailed experimental setup is shown in Fig. 5 and consists of the following three parts:

1) Generation of optical return-to-zero (RZ) signal

The 1552.5 nm-wavelength continuous-wave (CW) is output from an optical transmitter and then be amplified by erbium doped fiber amplifier (EDFA1) with 15 dBm saturation power to compensate for the insertion loss of Mach-Zehnder interferometer (MZI) modulators. The tunable bandpass filter (TBPF1) of 1 nm bandwidth is used to reduce amplified spontaneous emission (ASE) noise. In order to generate an optical RZ signal, an optical carrier is, respectively, intensity-modulated by MZI modulators using a 10 GHz non-return-to-zero (NRZ) pseudo random binary sequence and 10 GHz clock signal. Due to the polarization dependence of the modulators, two

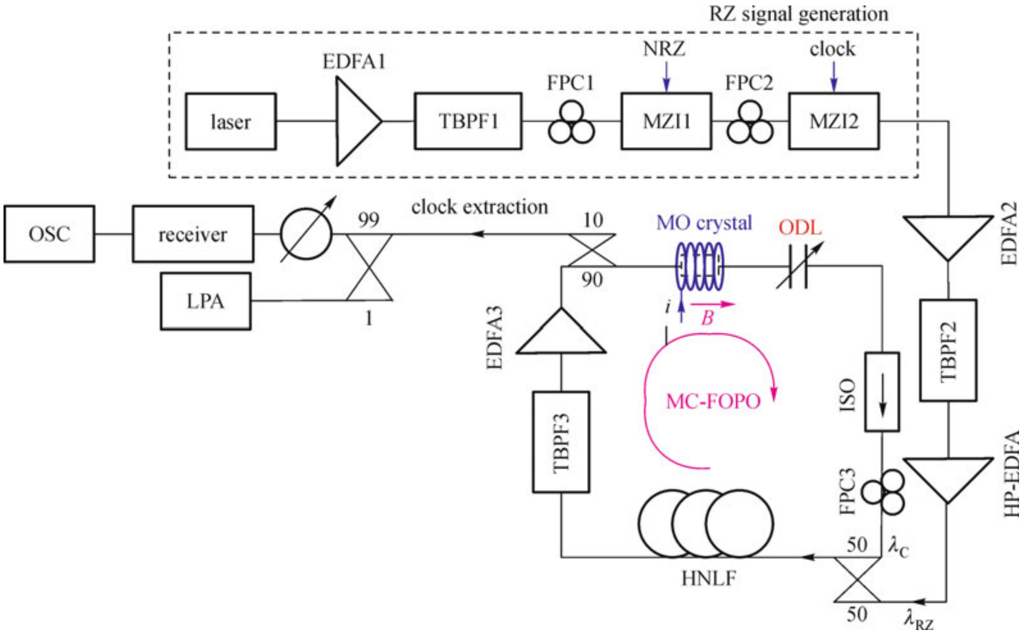


Fig. 5 Schematic diagram of MC-FOPO

fiber polarization controllers (FPC1, FPC2) are used to adjust the state of polarization (SOP) of light. The high-power optical RZ signal as pump light is obtained by high-power EDFA (HP-EDFA) and then coupled into the FOPOs cavity via a 50/50 optical fiber coupler.

2) Magnetically controllable fiber loop

In the HNLF, the pump light input to the fiber loop and the ASE light as seed source will take part in the parametric process. A tunable ODL is used to adjust the FOPO cavity length to match the input pump signal. In this case, the clock can be extracted if the parametric gain provided by the parametric process is large enough. The central wavelength of the output clock signal can be selected by tuning TBPF3. EDFA3 in the fiber loop is used to compensate for the cavity loss. As a magnetic control component in the cavity, the centralized magneto-optic crystal unit is controlled by the external magnetic field of the solenoid. The magnetic field can be changed from 0 to 200 Gs, corresponding to the drive current (*i*) from 0 to 2.5 A.

3) Clock signal detection

A 90/10 coupler is used to extract 10% of the oscillating-signal power as the clock output, in which 1% of the output is monitored by an Agilent light polarization analyzer (LPA) to analyze the effect of the magnetic field on the polarization state through a 1/99 coupler. The other 99% is sent to an oscilloscope (OSC) via a receiver to show eye diagrams and waveforms.

4 Experimental results and discussion

A spool of 500 m HNLF is used in the experiment with a dispersion of 0.5 ps/(nm·km) and a dispersion slope of 0.028 ps/(nm^2·km) at 1550 nm. In the absence of the drive current, an optimal eye diagram of the output clock signal can be obtained by tuning the ODL and the FPC together, as shown in Fig. 6(a), with the received optical power of 4.8 dBm. Figure 6(b) shows the deterioration of the eye diagram induced by the current change from 0 to 2.5 A. A good eye diagram can be achieved again by adjusting the FPC and the ODL, as shown in Fig. 6(c). It is proven that the external magnetic field not only changes the polarization state of guided optical wave, but also influences the effective cavity length of FOPOs through magnetically circular birefringence. As the current is adjusted from $i =$ 2.5 to 0 A then 2.5 A, the eye diagram changes from Figs. 6(c) to 6(e), which proves the MC-FOPOs have a good magnetic tunability and repetition desirable for all OCR. We deduce that the magnetic field changes the refractive index of the magneto-optic crystal and therefore changes the optical path. In other words, the magnetic control method can compensate for the cavity length drift induced by other factors and then improve the stability of FOPOs. At the same time, the magnetic control method has some unique advantages such as non-mechanical control, high precision, fast response to control signal, and good repetitive operation.

5 Conclusion

In this paper, we investigate the magnetic control method used in FOPOs to directly extract the optical clock from the optical RZ signal. The magnetic tunability for MC-FOPOs is demonstrated by our experiment. The magneto-optic

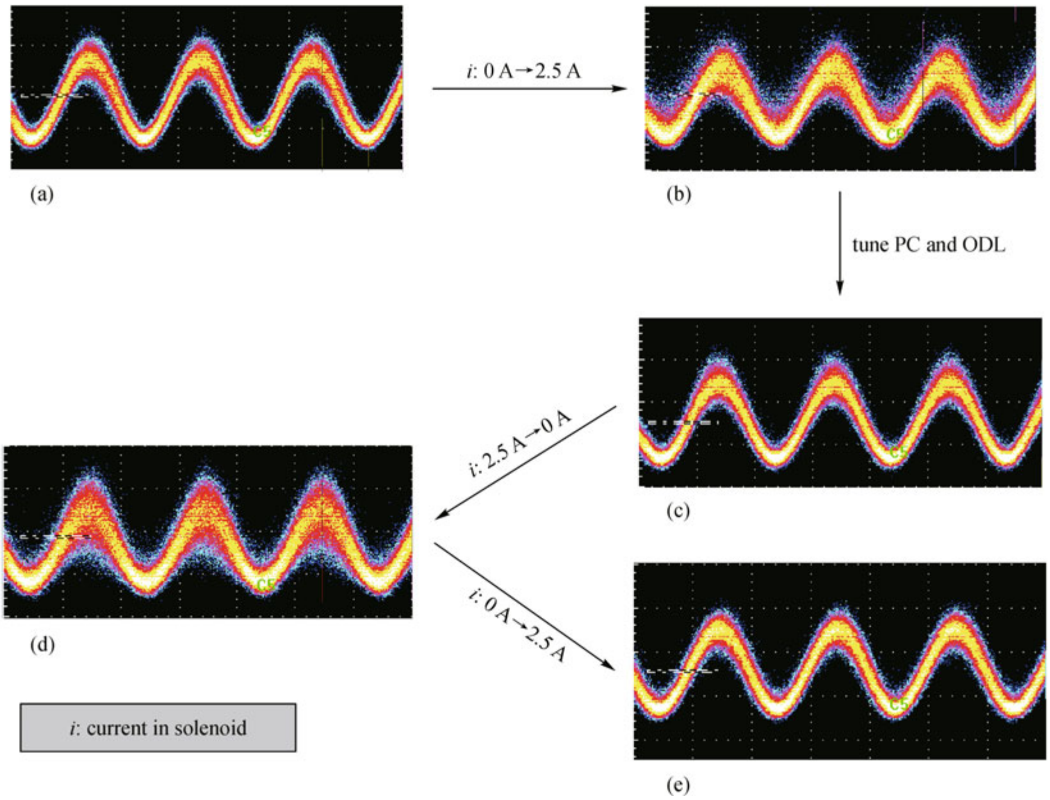


Fig. 6 Eye diagrams of clock extraction. (a) Optimal eye diagram when $i = 0$ A; (b) adjust i to 2.5 A; (c) optimal eye diagram by tuning PC and ODL; (d) adjust i to 0 A; (e) adjust i to 2.5 A

crystal unit used in the MC-FOPOs can be regarded as the combination of the fiber polarization controller and the ODL and is capable of compensating for the drift of cavity length. Our experimental results show the feasibility of the magnetic control method for the optical clock extraction. Moreover, some unique advantages of the MC-FOPO structure are also useful for the theoretical research on the magnetic control of fiber nonlinearity.

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