Differential all-birefringent-fiber frequency-modulated continuous-wave Sagnac gyroscope

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Abstract. A differential all-birefringent-fiber frequency-modulated continuous-wave Sagnac gyroscope is described. The gyroscope employs a birefringent fiber coil to construct a double unbalanced fiber optic Sagnac interferometer and uses the phase difference between the two beat signals from the fiber coil to measure the rotation velocity. The advantages of this gyroscope include doubled rotation sensitivity and less nonreciprocal phase drift.
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Fiber optic gyroscopes are recognized as the most successful fiber optic sensors. Fiber optic gyroscopes have a number of advantages over the mechanical counterparts, such as small size, no moving parts, better reliability, and rapid initiation. Early model fiber optic Sagnac gyroscopes simply use a fiber coil instead of the single closed air path defined by mirrors, so that the Sagnac effect can be multiplied by the number of fiber loops, which is typically a few thousands.[1] However, such fiber optic Sagnac gyroscopes suffer from the problems of zero-sensitive point (i.e., the sensitivity is zero as the rotation velocity approaches zero) and ambiguities in fractional phase calibration, phase shift direction determination, and full period count. Modern fiber optic Sagnac gyroscopes are based on the principle of phase modulation interference.[2–4] They use a phase modulator located near one end of the fiber coil to dynamically modulate phase difference of the two counter-propagating beams. Phase-modulated fiber optic Sagnac gyroscopes can overcome the problem of zero-sensitive point, but the dynamic range of the gyroscopes normally is limited to a $\pm\pi/2$ phase shift.

Optical frequency-modulated continuous-wave (FMCW) interference, a new technology derived from radar, naturally produces a dynamic signal, and thus to calibrate the fractional phase, distinguish the phase shift direction, and count the number of the full periods is much easier.[5–7] The application of optical FMCW interference to rotation sensing not only can solve the problems in the conventional fiber optic gyroscopes, but also can reduce the size and weight because the fiber optic FMCW gyroscope does not use bulk phase modulators or frequency shifters.

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The essential requirement for a fiber optic FMCW Sagnac gyroscope is that the gyroscope should be unbalanced, so that the beat signal with a proper frequency can be obtained. This requirement, however, makes the fiber optic gyroscope complicated and introduces a nonreciprocal phase drift in the fiber optic gyroscope if the surrounding parameters (such as temperature) change.[8] Birefringent fibers can support two orthogonal polarization modes with different propagation numbers. This implies that a single length of birefringent fiber can be used as a double-beam unbalanced interferometer if the light is coupled into its two orthogonal polarization modes. Therefore, for the birefringent fiber FMCW Sagnac gyroscope, it is not necessary to build an extra fiber network to introduce an optical path difference offset. However, the nonreciprocal phase drift due to the extension of birefringent fiber coil still exists.[9] This letter reports a differential all-birefringent-fiber FMCW Sagnac gyroscope, which can eliminate the nonreciprocal phase drift and double the sensitivity as well.

Figure 1 shows the optical setup of the differential all-birefringent-fiber FMCW Sagnac gyroscope, which comprises a polarized FMCW laser, a polarization-maintaining fiber coupler (PMFC), a birefringent fiber coil, a polarization beam splitter (PBS), and two photodetectors (D_1 and D_2). The output fibers of the PMFC are connected with the birefringent fiber coil in the same polarization directions, but the coordinates of the principal axes on the two ends of the birefringent fiber coil have a 90-deg rotation.

The polarized FMCW laser beam is first coupled into one input fiber of PMFC in both polarization modes (i.e., the HE_{11}^x mode and the HE_{11}^y mode), and divided into two beams propagating along the two output fibers. These two beams are then coupled into the birefringent fiber coil in two polarization modes from the different ends. Since the principle axes on the two ends of the birefringent fiber coil have a 90-deg rotation, the clockwise-propagating HE_{11}^x mode beam and the anticlockwise-propagating HE_{11}^y mode beam will vibrate in the same direction after exiting the birefringent fiber coil and produce the first beat signal, while the clockwise-propagating HE_{11}^y mode beam and the anticlockwise-propagating HE_{11}^x mode beam will vibrate in

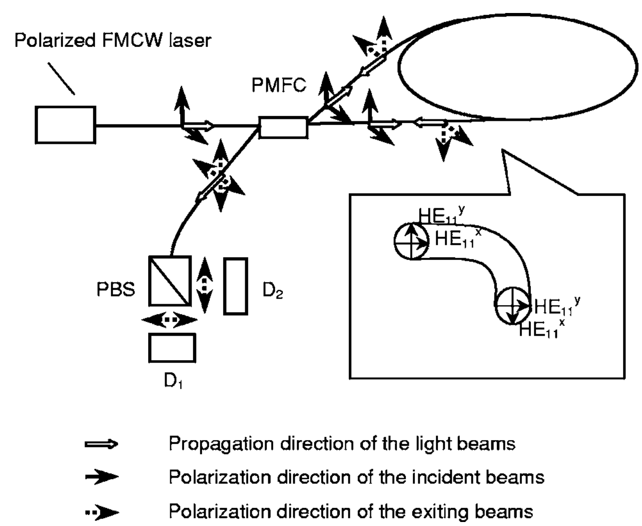

Fig. 1 Differential all-birefringent-fiber FMCW Sagnac gyroscope.

another orthogonal direction after exiting the fiber coil and produce the second beat signal. These two optical beat signals are naturally perpendicular to each other, so that they can be separated by the PBS. The separated two beat signals are finally detected by D_1 and D_2.

Obviously, these two beat signals have an opposite optical path difference (*OPD*) offset, which can be written as

$$OPD = \pm (n_{ex} - n_{ey})L, \tag{1}$$

where n_{ex} and n_{ey} are the effective refractive indexes of the HE_{11}^{x} mode and the HE_{11}^{y} mode, respectively, and L is the length of the birefringent fiber coil. However, since the Sagnac effect is not influenced by the refractive index of the dielectric medium,[10] if the birefringent fiber coil is in rotation, the two beat signals will have the same Sagnac phase shift, which can be written as

$$\delta\phi_s = \frac{4\pi RL\Omega}{c\lambda}, \tag{2}$$

where R is the radius of the fiber coil, Ω is the rotation angular velocity component parallel to the coil axis, c is the speed of light in free space, and λ is the optical wavelength in free space.

The signal analysis of optical FMCW interference has been performed elsewhere.[7] If the frequency of the light source is modulated with a sawtooth waveform, for instance, the intensity of the detected beat signal $I(t)$ in a modulation period can be written as

$$I(t) = I_0\left[1 + V\cos\left(\frac{2\pi\Delta\nu\nu_m OPD}{c}t + \frac{2\pi}{\lambda_0}OPD + \frac{4\pi RL\Omega}{c\lambda_0}\right)\right], \tag{3}$$

where I_0 is the average intensity, V is the contrast, $\Delta\nu$ is the optical frequency modulation excursion, ν_m is the modulation frequency, and λ_0 is the central optical wavelength in free space. For the beat signal with a negative *OPD* offset, the intensity can be rewritten as

$$I(t) = I_0\left[1 + V\cos\left(\frac{2\pi\Delta\nu\nu_m |OPD|}{c}t + \frac{2\pi}{\lambda_0}|OPD| - \frac{4\pi RL\Omega}{c\lambda_0}\right)\right]. \tag{4}$$

Obviously, the phase difference of the two beat signals $\Delta\phi$ equals

$$\Delta\phi = \frac{8\pi RL\Omega}{c\lambda_0}. \tag{5}$$

Hence, the rotation angular velocity of the birefringent fiber coil can be determined by

$$\Omega = \frac{c\lambda_0}{8\pi RL}\Delta\phi. \tag{6}$$

Compared with conventional fiber optic Sagnac gyroscopes, it can be seen that the differential all-birefringent-fiber FMCW Sagnac gyroscope has a doubled sensitivity. Note that, since the $\Delta\phi$ is not relative to *OPD*, this gyroscope is not affected by the length variation of the fiber coil due to temperature change or strain.

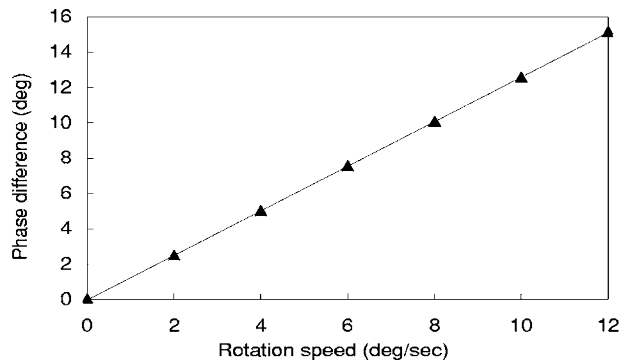

Fig. 2 Relationship between the rotation angular velocity of the birefringent fiber coil and the phase difference between the two beat signals.

The primary experiment is performed with a single-mode 660-nm laser diode with an optical fiber pigtail, a silicon p-i-n photodiode, a 50/50 polarization-maintaining fiber coupler, and a 100-m elliptical-core birefringent fiber coil of 0.1 m in radius. The optical frequency of the laser diode is modulated with a sawtooth waveform at a frequency of 10 kHz by modulating its driving current. The two beat signals are sent to two bandpass filters to choose the most intensive harmonic components to compare the phase difference with each other. Figure 2 shows the linear relationship between the phase difference of the two beat signals and the rotation angular velocity of the gyroscope. The experimental results demonstrate a resolution of 0.01 deg/s.

In conclusion, the first differential all-birefringent-fiber FMCW Sagnac gyroscope is proposed and demonstrated. The experimental results prove that this fiber optic gyroscope has several advantages, such as double sensitivity, long dynamic rang, and less nonreciprocal phase drift. Moreover, because of the all-fiber structure, the gyroscope is very stable and compact.

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