LOW COST FIBER OPTIC ANGULAR VELOCITY SENSOR

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ABSTRACT

This paper reports the construction of a low cost open loop optical sensor to measure angular velocities. The operation of the system is based on Sagnac effect in a fiber ring interferometer. The sensitivity of the device was measured as 0.04deg/sec while the operation limits was observed as ±26deg/sec. To enhance the sensitivity and to force the system to operate in the linear region a dynamic phase modulation using a piezoelectric ceramic has been incorporated to the sensor.

I. INTRODUCTION

Guidance and navigation systems in aeronautics, naval and space systems for civilian and military applications require very sensitive angular velocity sensors. There are four angular velocity sensor technologies: dynamically tuned gyroscope (DTG) [1], micro-electro-mechanical system (MEMS) [2], ring-laser gyroscope (RLG) [3] and fiber-optic gyroscope (FOG) [4]. Fiber optic gyroscopes, which have wide application areas and plays a critical role among the other angular velocity sensors they the most preferable and advantages ones. In comparison with the current angular velocity sensors, fiber optic angular velocity sensor has technological superiorities [5].

The fiber optic angular velocity sensors advantages are[6];

- No moving parts
- Not sensitive to shocks and vibrations
- Not sensitive to gravity nor accelerations
- No locking problems
- Short initialization time
- Good sensitivity
- Long lifetime and high reliability
- Low power consumption
- Wide dynamic area

Detection of rotation with light was demonstrated by Sagnac [7] in 1913 while he was observing the effect of the relative motion of the ether. Sagnac demonstrated that it is possible to detect rotation with respect to inertial space with an optical system that has no moving part. The original setup was very far form practical angular velocity sensor, because of its very limited sensitivity. In 1962, Rosenthal [3] proposed to enhance the sensitivity with a ring cavity instead of the Sagnac interferometer and after 1963, it was used in many practical applications [8][9]. The RLG(Ring Laser Gyroscope) is the most mature technology in terms of its development [12]. With the invention of low-loss optical fiber and solid-state semiconductor light sources and detectors, V. Vali and R. W. Shorthill [4] demonstrated the first interferometric fiber optic gyroscope (IFOG) in 1976.

II. SAGNAC EFFECT

Fiber optic angular velocity sensor is based on the Sagnac effect, which produces a phase difference $\Delta\phi_R$ proportional to the rotation rate Ω in a ring interferometer.

To get a better understanding of Sagnac effect, consider a hypothetical interferometer with a circular optical path in vacuum (Fig. 1). Two beams of light waves are sent in opposite directions around a ring. When the interferometer is at rest in an inertial frame of reference the path lengths of the counterpropagating waves are equal and, since light travels at the same speed c in both directions around the loop, both waves return to the point of injection P_i in phase after a propagation time $\tau = 2\pi R/c$ where R is the path radius. When the interferometer is rotating at a rate Ω and the observer is motionless in the original frame, the point P_i moves through an angle Ω_T during the propagation time τ [10][11]. Therefore, the difference between the propagation times of the counterpropagating waves are.

$$\Delta\tau = \frac{(2\pi + \Omega\tau)R}{c} - \frac{(2\pi - \Omega\tau)R}{c} = \frac{4\pi R^2\Omega}{c^2} \qquad (1)$$

For continuous waves of angular frequency ω, this corresponds to a phase shift of

$$\Delta\phi = \omega\Delta\tau = \frac{4\pi R^2\omega}{c^2}\Omega . \qquad (2)$$

Since the Sagnac effect is proportional to the flux of the angular velocity vector **Ω**, it can be enhanced with a multiturn path. A multiturn single-mode fiber coil may provide adequate sensitivity. The Sagnac phase difference becomes

$$\Delta\phi_R = \frac{2\pi LD}{\lambda c}\Omega \tag{3}$$

where λ is the wavelength in a vacuum, D is the coil diameter, $L=N\pi D$ is the fiber length, and N is the number of turns. The coefficient $(2\pi LD/\lambda c)$ is call the scale factor of the gyroscope.

$$SF = \frac{2\pi LD}{\lambda c} \tag{4}$$

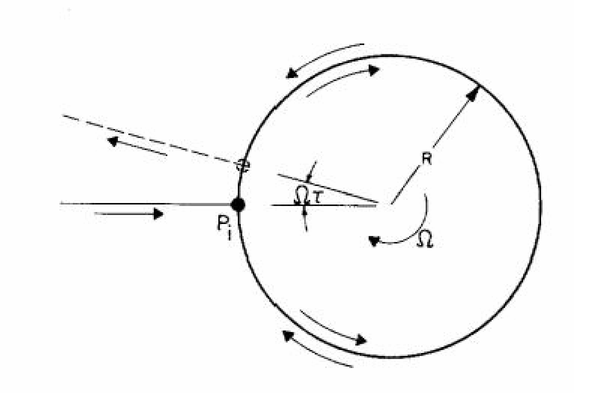

Figure. 1. Sagnac effect in a circular path.

The detected light with a photo detector is the familiar raised cosine function of a two-beam interferometer [11].

$$P_D = \frac{P_0}{2}\left[1+\cos\Delta\phi_R\right] \tag{5}$$

where P_0 is the maximum detector power and $\Delta\phi_R$ is the Sagnac phase difference. With no rotation the maximum amount of light returns to the detector and the detector power is at its maximum P_0. With increasing angular velocity the detector power gradually decreases and reaches zero at $\Delta\phi_R = \pm\pi$ [12]. There is an unambiguous range of phase measurement of $\pm\pi$ rad around zero and operating range of $\pm\Omega_\pi$ for angular velocity [10],

$$\Omega_\pi = \frac{\lambda c}{2LD} \tag{6}$$

Due to the cosine shape, the change in interferometer output is small for small input angular velocity. If the total phase difference is much less than 1rad, the cosine will be near its maximum value and the detected power will not be sensitive and it would not be possible to determine the sign of the Sagnac phase shift. To overcome these problems, a biasing phase difference can be used to shift the operating point portion of the raised cosine where the response is quasi-linear [12][13]. There are two phase biasing techniques, static and dynamic phase modulation. An optic phase modulator is placed in the end of the sensing fiber coil and driven by a sinusoidal or square wave signal to provide the phase shift.

III. DESCRIPCION OF THE SYSTEM

In order to reduce to optical configuration complexity and the cost, a minimum configuration has been proposed. A photograph of a prototype of our angular velocity sensor is presented in Fig. 2 and a schematic diagram of the optical circuit is illustrated in Fig. 3.

Tracing the optical circuit, light leaves the LED light source and enters to the monomode fiber and moves to the 2x2 directional coupler. Here half of the light is directed to the polarizer. The light leaving the polarizer enters to a second 2x2 directional coupler, then travels through the 1000 meters optical fiber coil and goes into the phase modulator. The combined wave in the optical coupler enters to the detector and its amplifitied and demodulated.

An InGaAsP edge emitting LED was chosen as the systems light source. It operates at 1310nm wavelength and its spectral width is 40nm and provides an output power of 10μW at 1310nm. The LED has an ST type connector which is suitable to the optical fiber which we used to make the fiber coil.

Figure. 2. Prototype of the sensor.

The sensor coil consists of 1000 meters of ALCATEL model SM type E monomode optical fiber wound around a 12.3cm diameter plastic spool. It has an attenuation of 0.328dB/km at 1310nm. The core diameter and cladding diameter are 9.3µm and 125µm respectively. The sensors scale factor with this fiber coil was calculated as 1.966 using eq. 4. and the dynamic range as 91.53deg/sec using eq. 6.

The photodetector is an InGaAs detector which is suitable to operate at 1310nm and has a differential output.

Two 2x2 directional optical couplers with a %50/%50 splitting ratio at 1310nm±40nm are used. The coupling loss is 3.6dB and two ports of the coupler has FC type connector the other two ports has ST connector type.

An in-line polarizer operating 1310nm with an insertion loss 0.8dB and extinction ratio 26dB is used. Both ports of the polarizer have FC type connectors.

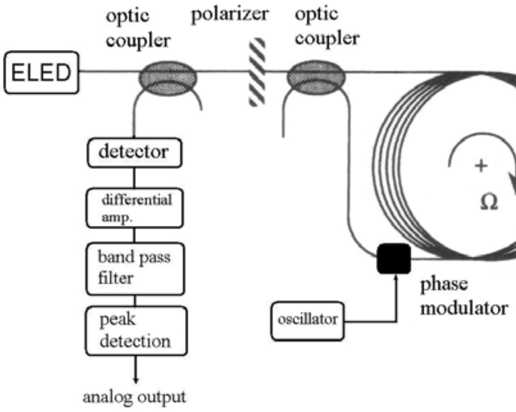

Figure. 3. Schematic diagram of the sensor.

In order to move the operating point to a linear and sensitive region a dynamic phase modulator is introduced to the system. A 25mm diameter and 0.5mm thick PZT piezo buzzer which is mounted on metal disk of 50mm diameter with a resonant frequency of 3kHz is used. Maximum $30V_{PP}$ voltage can be applied to the buzzer. Since the thickness of the PZT is not enough to wind the fiber cable several turns, a plastic of 10cm in diameter and 4cm thick is used to wind the cable. A slot is opened and the buzzer is placed in the slot as shown in Fig. 4. With this system when the sensitivity is adjusted to a maximum level the operation interval would be 1.8rad to 1.34rad. which correspond to an angular velocity of 39deg/sec.

Figure. 4. Optic phase modulator.

IV. PERFORMANCE RESULTS

To test the performance of the sensor, the system is placed on a rotating platform whose angular velocity can be controlled and measured. The voltmeter output connected to the analog output of the detector measure the light intensity. The angular velocities of the rotating platform have also been recorded. The output voltage vs. to the angular velocity have been plotted in Fig. 5 and Fig. 6 for clockwise and counterclockwise rotational directions. The figures illustrate an excellent linearity up to 10deg/sec. After 10deg/sec the linearity is not excellent.

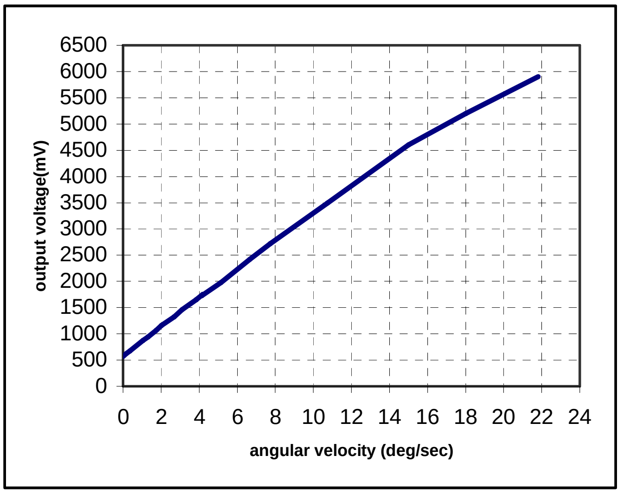

Figure. 5. Output voltage vs. angular velocity for clockwise rotation.

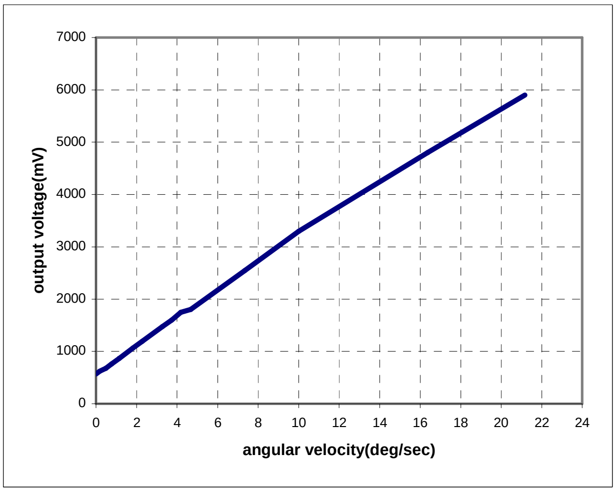

Figure. 6. Output voltage vs. angular velocity for counterclockwise rotation.

V. CONCLUSION

A minimum configuration open loop fiber optic angular velocity sensor has been constructed and evaluated. The performance and cost of this configuration make it very attractive for use in land navigation and robotics applications. The experimental results show that the sensitivity of our system is 0.04deg/sec and the range is

±26deg/sec. The range can be increase up to ±39deg/sec by chancing the amplification of the detection system. The performance can further be increased using temperature controlled broad band LED. Low attenuation polarizer can also enhance the performance. Also instead of using connectors the fibers can be fusion fused. For the phase modulation and demodulation phase locked loop can be applied.

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