Invited Paper

Sensing and Instrumentation Applications of the Sagnac Fiber Optic Interferometer

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ABSTRACT

The Sagnac interferometer has been used to support fiber optic gyros to sense rotation which currently represents the largest single market for fiber sensors. The Sagnac fiber optic interferometer may also be used to sense time varying and very slowly varying environmental effects as well as instrumentation to measure the properties of light sources and optical fiber. This paper provides an overview of these and other applications of the Sagnac fiber optic interferometer.

1. INTRODUCTION

The Sagnac fiber optic interferometer has primarily been investigated to support rotation sensing[1-6] and is beginning to replace mechanical and ring laser gyros in traditional application areas as well as opening new navigation and guidance opportunities due to its solid state, environmentally rugged nature. Less well known applications include acoustic and strain sensing. In the area of acoustic sensing[7-9] the Sagnac fiber optic interferometer offers optical filtering of low frequency signals and position sensitive sensing that may be used to support distributed sensing applications[10-11]. These advantages could be used to support sensing of any time varying phenomenon. For slowly varying phenomena a frequency shifter may be added to the loop so that the entire Sagnac loop is sensitive to length changes[12]. This approach allows the potential of very long strain gauges. Finally the Sagnac interferometer may be used as an instrument to study dispersion characteristics of optical fiber and as a spectrometer to measure the central wavelength of broadband light sources[13,14]. The following sections of the paper will overview the operation of the Sagnac fiber optic interferometer for these applications.

2. ROTATION SENSING

The Sagnac fiber optic interferometer offers the world the first solid state high performance rotation sensor. Because of very large market potential for guidance and navigation of aircraft and spacecraft there has been tremendous activity in the this field since the first hardware demonstration by Vali and Shorthill[15] in 1976. This has resulted in numerous companies worldwide[16-21]entering fiber optic gyroscopes into the marketplace in some cases with entirely new applications such as automobile navigation[20].

The basic Sagnac effect is illustrated by Figure 1. Light propagates around a closed path which in the case of Figure 1 is a circle in opposite directions. If the two counterpropagating light beams originate from the same point and the circle of radius R rotates at Ω then the clockwise light beam traverses a path $2\pi R + \Omega RL/c$ while the counterclockwise light beam traverses a path $2\pi R - \Omega RL/c$. The net path difference is then just $2\Omega RL/c$. Dividing this result by the wavelength of light results in

$$Z_R = 2\Omega RL/(\lambda c) \tag{1}$$

where Z_R is the fringe shift due to rotation. This equation is the fundamental equation for the open loop fiber optic gyro. If nothing else is done when rotation occurs interference patterns will result in cosinsoidal output when the two counterpropagating beams recombine. For high performance wide dynamic range applications this is

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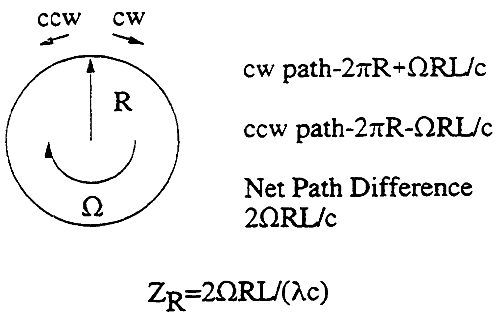

Figure 1. The Sagnac Effect.

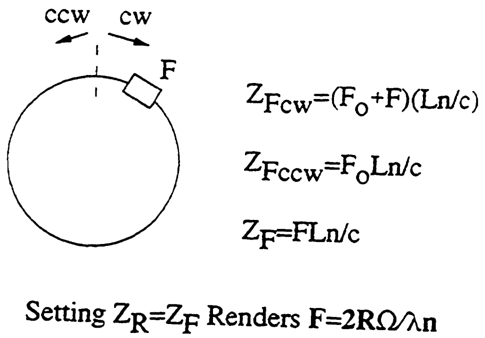

Figure 2. Counterbalancing frequency induced phase shifts.

undesirable. To circumvent this problem a frequency shifter may be inserted into the Sagnac loop as shown in Figure 2. In this case the clockwise propagating light beam circulates about the loop at a frequency $Z_{Fcw}=(F_o+F)/(Ln/c)$ while the counterclockwise propagating light beam circulates at $Z_{Fccw}=F_oLn/c$. The net frequency induced fringe shift is then just $Z_F=FLn/c$.

If the rotationally induced fringe shift is set equal to the frequency induced fringe shift so that a constant position on the fringe is maintained then

$$F = 2R\Omega / \lambda n \tag{2}$$

This is the fundamental equation for the closed loop fiber optic gyro and also happens to be the equation which governs the operation of the ring laser gyro[22].

Figure 3 illustrates the layout of the open loop fiber optic gyro. A light source with a low coherence length such as a light emitting diode is used so that interference from coherent backscatter is minimized[23-24]. The light beam is coupled into a fiber beamsplitter and passes through a polarizer before entering a second beamsplitter which acts to generate counterpropagating light beams. The use of the dual beamsplitter configuration in combination with the polarizer is used to ensure that the light beams traverse identical paths when they counterpropagate through the Sagnac loop[25]. A modulator is placed in the Sagnac loop offset from the center position to generate a time varying demodulation signal.

If the modulator is driven at a frequency ω and the fiber gyro is not rotating then the action of the modulator will be to generate signals at second and higher order even harmonics of ω on the detector. In the presence of rotation there will be a relative phase shift between the counterpropagating beams and the action of the phase modulator will be to generate first and higher order odd harmonics of ω. The amplitude of these signals will depend on the rate of rotation and the phase will depend on the direction. Figure 3 illustrates how these detection signals are generated.

For the simplest open loop fiber gyros the output of the first or a higher order odd harmonic is used as the output. This results in a cosinusoidal output as is shown in Figure 4. For many applications such as pointing and tracking the open loop fiber optic gyro provides adequate linearity and dynamic range to meet system requirements. The inherent advantages of the fiber optic gyro which include very long lifetimes, fast turn on times and geometric packaging flexibility make these devices very competitive.

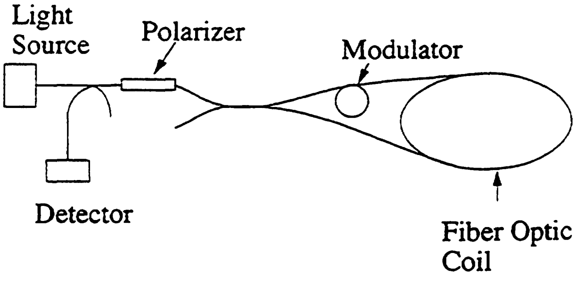

Figure 3. Open loop fiber optic gyro.

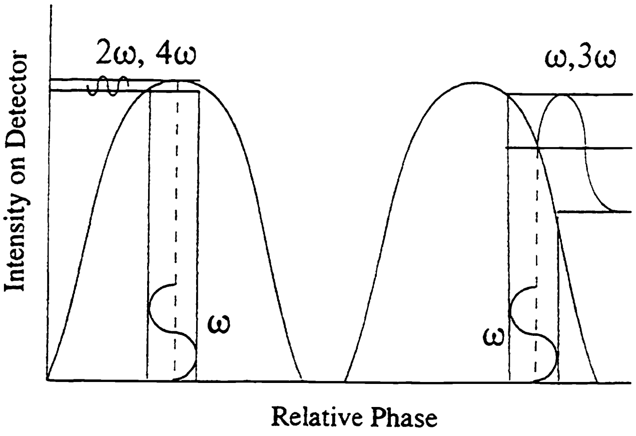

Figure 4. Open loop fiber optic gyro detection signals.

For applications that require improved performance in the form of wider dynamic range, better linearity and scale factor the closed loop fiber optic gyro is a better choice. Figure 6 shows the basic layout of the closed loop fiber optic gyro. In this case a frequency shifter has been added to the open loop configuration in combination with a synchronous demodulator, integrator and voltage controlled oscillator that act to adjust the frequency shifter operating frequency so that rotationally induced phase shifts are counterbalanced with frequency induced phase shifts[26-27]. This type of fiber optic gyro has become the standard for moderate to high performance navigation applications.

Currently the major competitors of fiber optic gyros are mechanical gyros and ring laser gyros. Mechanical gyros which have limited lifetimes due to bearing wear and also have problems associated with cold start up and excess acoustic noise are competing largely on the basis of cost. As fiber optic gyros become increasingly competitive through the usage of improved components produced in association with the telecommmunication and optoelectronic industry one can expect that fiber gyros will replace most mechanical gyros in new applications. Ring laser gyros are competitive because of their high end performance, notably with respect to scale factor. Because the ring laser gyro entered production about 15 year prior to the fiber optic gyro they also have the advantage of an established production base. Set up costs for producing fiber optic gyros are considerably lower than for ring laser gyros and this has resulted in a large number of companies entering the field and recent wins by fiber optic gyros over ring laser gyros in the moderate performance regime. As production continues to increase and performance enhancements are made through the use of improved components and designs it can be expected that fiber optic gyros

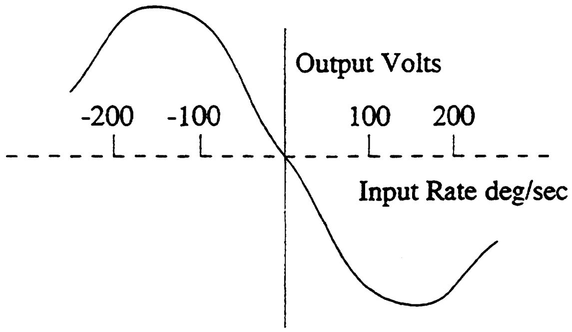

Figure 5. Open loop fiber optic gyro output.

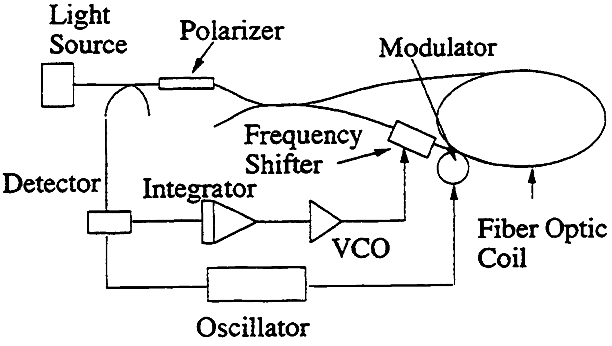

Figure 6. Closed loop fiber optic gyro.

will put considerable pressure on ring laser gyros because of inherent advantages with respect to cost and long term reliability.

3. TIME VARYING ENVIRONMENTAL EFFECTS

The Sagnac interferometer may be used to measure time varying environmental effects[7-8] such as acoustics by arranging the Sagnac loop so that the environmental effect to be measured impresses an induced phase difference between the counterpropagating light beams. The magnitude of the induced phase difference will depend on the position of the signal from the center of the Sagnac loop where the sensitivity is zero since both counterpropagating light beams arrive at the same time, the frequency of the signal and its amplitude.

Figure 7 illustrates the layout of a Sagnac interferometer for sensing time vary environmental effects such as acoustics. In general part of the fiber is shielded or desensitized to the effect to be measured while the other portion of the fiber is optimized for sensitivity to it. Figure 8 illustrates the effect of shielding and position. If the entire coil is exposed to the environmental effect simultaneously there will be equal and opposite induced signals from each side of the coil and the net phase shift will be zero. Fiber gyro manufacturers are particularly interested in fiber coil layouts that are designed to first order cancel time varying effects. For the acoustic sensor designer that problem is how to optimize sensitivity and shielding on half of the coil is a way to proceed. Another method is to use a push pull configuration with opposite effects on each side of the coil.

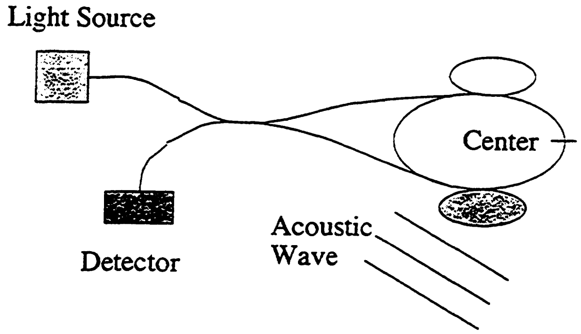

Figure 7. Measurement of time varying environmental effects.

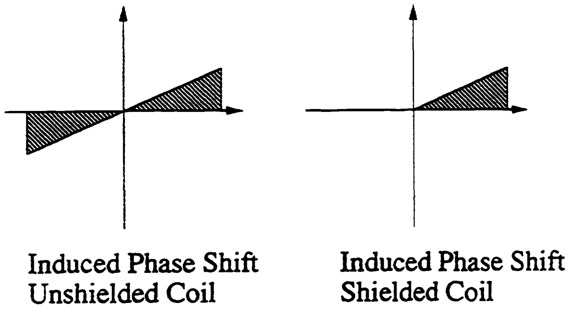

Figure 8. Effect of shielding/position.

It is possible to quantify time varying effects. Consider the diagram in Figure 9 where an element dy along the Sagnac loop is a distance y from the central beamsplitter. For a coil of length L and a time varying phenomena P which might be pressure the net effect on the element dy is

(3)
$$\left(\frac{yn}{c}-\frac{(L-y)}{c}n\right)\frac{dP}{dt}$$

and if the response of the fiber is given by G(y,P) then the total response over the fiber coil is given by

(4)
$$R[P(t)]=\int_0^L\left[G(y,P)\bullet\frac{dP}{dt}\bullet(2y-L)\bullet\frac{n}{c}\right]dy$$

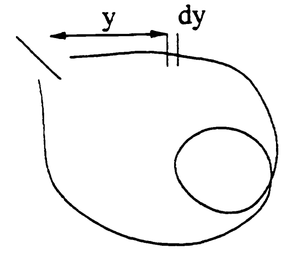

Figure 9. Calculation of time varying effects.

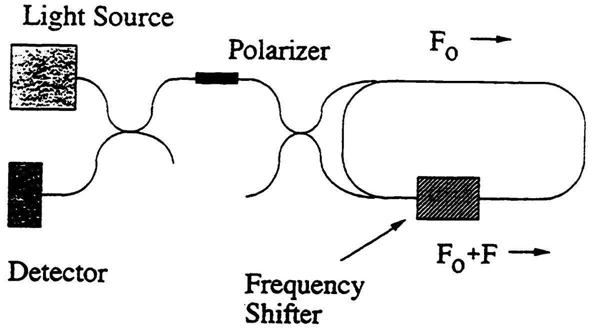

Figure 10. Measurement of slowly varying effects.

A couple simple examples are instructive. If $G(y,P)=A=\text{constant}$ over the Sagnac loop length then $R[P(t)]=0$ which is what a good fiber gyro coil design would like to achieve. If $G(y,P)=0$ over $0<y<L/2$ and $G(y,P)=A=\text{constant}$ for $L/2<y<L$ then $R[P(t)]=[AnL^2/4c]dP/dt$ and for $P=\sin(\omega t)$, $R[P(t)]=[ABnL^2/4c]\omega \sin(\omega t)$. This equation will apply as long as the frequency of the environmental effect is small compared to the characteristic frequency of the Sagnac loop which in many cases holds. Note that the sensitivity is proportional to ω and the square of the length L. These features give the designer considerable flexibility in optically filtering the time varying signal.

4. SLOWLY VARYING ENVIRONMENTAL SIGNALS

Some environmental parameters such as strain do not vary rapidly with time. The Sagnac interferometer may be used to measure these parameters as well by placing a frequency shifter in the loop so that a frequency difference F is generated between the counterpropagating light beams as shown in Figure 10. In this case the fringe shift due to the frequency difference is $Z_F=F(Ln/c)$ and if Z_F is held constant then $0=dF(Ln/c)+FdL(n/c)$ or $dF/F=-dL/L$. As an example by using an acoustooptic modulator with an operating frequency of 100 MHz in a Sagnac loop capable of resolving a frequency change of 1 Hz changes on the order of 1 part in 10^8 of the length L could be measured. One very interesting aspect of this type of sensor is that it has the potential to be used as a very long strain gauge. This could be used to measure strain on power lines, or bridge cables. It could also be used for strain build up measurements in earthquake prone areas or changes in the profiles of volcanoes before they erupt[28].

5. DISTRIBUTED SAGNAC SENSING

Since the time varying Sagnac interferometer configuration is position sensitive it may be used to determine the position and location of a time varying disturbance by using multiple interferometer configurations. One of the first configurations to demonstrate this was a combination of a Sagnac and Mach-Zehnder interferometer proposed by Dakin et. al.[10] and shown in Figure 11. The Mach-Zehnder is used to measure the amplitude of the signal and the ratio of the Sagnac and Mach-Zehnder signals is used to measure position. An alternative approach shown in Figure 12 is to switch the Sagnac interferometer between the quasi-static and time varying regime and compare the signal levels to measure amplitude and position by using switches to operate and bypass a frequency shifter in the Sagnac loop. It is also possible to use wavelength division multiplexed Sagnac interferometers as shown in Figure 13. Here the sum of the two signals would be used as a measure of the amplitude of the signal and the ratio would be used to determine position. An application of these distributed sensors is shown in Figure 14 where acoustic disturbances would be used to locate the position of a leak in a pressurized tank.

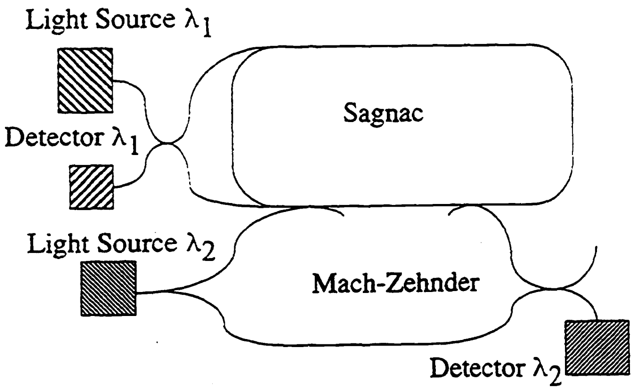

Figure 11. Sagnac/Mach-Zehnder distributed sensor

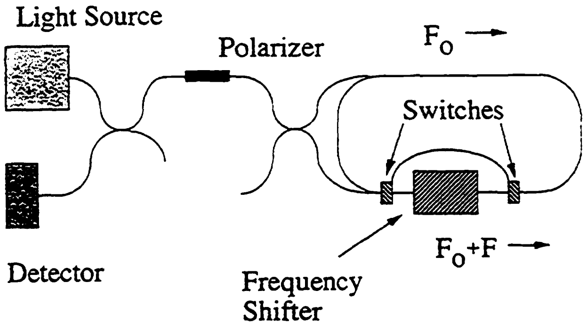

Figure 12. Distributed Sagnac sensor based on switched modes.

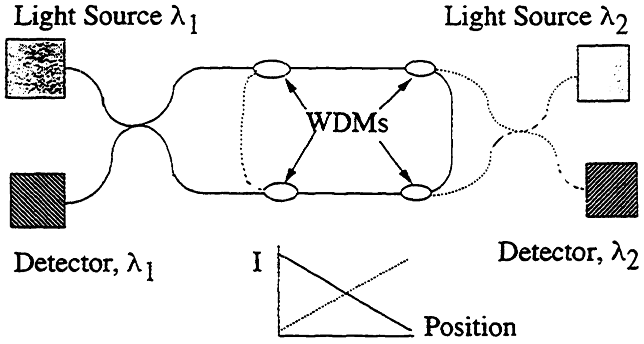

Figure 13. Wavelength division multiplexed Sagnac distributed sensor.

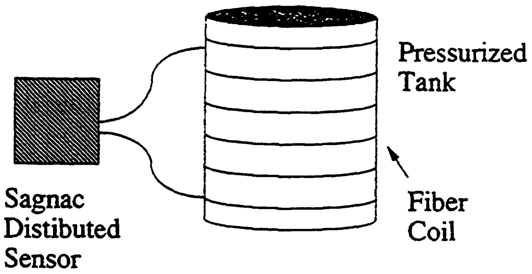

Figure 14. Detection of leaks in a pressurized tank.

6. SPECTRAL MEASUREMENTS

By introducing controllable frequency differences between the counterpropagating light beams in a Sagnac loop it is possible to scan through a series of fringes[12-14]. Dispersion in the fiber optic coil results in a wavelength dependence of the frequency separation between fringes. By using large frequency differences the Sagnac interferometer may be used as a spectrometer to characterize light sources or alternatively with a well calibrated light source may be used to measure dispersion effects in optical fiber.

7. SUMMARY

The Sagnac interferometer may be used to measure a wide variety of environmental effects and can be specifically configured to measure rapidly or slowly varying phenomenon. Its position sensitive response enables distributing sensing capability and it has the potential to be used as an instrument for spectral characterization of light sources and optical fiber.

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