Invited Paper

A Personal Tour of the Fiber Optic Sagnac Interferometer

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ABSTRACT

It has been over 30 years since the first fiber optic Sagnac interferometer was demonstrated by Vali and Shorthill in 1976 and the invention of the closed loop fiber optic gyro by Udd and Cahill in 1977. In these years the Sagnac interferometer in the form of the fiber optic gyro became and remains perhaps the most successful fiber optic sensor development. However it is not the only application of the fiber optic Sagnac interferometer and this paper is a personal tour of some other applications that include its usage for acoustic, strain, vibration, distributed sensing, intrusion detection and intrusion prevention. This paper is not intended to be a compressive review of the fiber optic Sagnac interferometer, instead it is a brief overview of a personal effort to develop fiber optic sensors and intrusion resistant communications systems based on this amazing interferometer with the help of friends at McDonnell Douglas, Blue Road Research, Columbia Gorge Research and a great deal of input from researchers worldwide.

Keywords: Sagnac, interferometer, gyro, rotation, acoustics, distributed, intrusion, secure communication

INTRODUCTION

If someone had told me in early September 1977 that the fiber optic sensor technology I was just beginning to explore would in just a few weeks begin to dominate my career and would remain my primary area of interest for more than 30 years I would have had a great deal of difficulty believing it. Space, astronomy and optics were elements of what I wanted to do growing up in the 1960s but my exposure to fiber optics did not occur until I started to work for McDonnell Douglas Astronautics Company (MDAC) in Huntington Beach, California in September 1977. My first effort there involved designing a fiber optic face placed based microscope that could be used for easy inspection of cryogenic foam being developed for liquid natural gas tankers and was completed in about two weeks at which point I had safely handed off building a series of devices to an optical technician. Evidently Richard Cahill who ran the Electro-Optics Lab there at the time was impressed enough that he decided to hand me a new project that involved looking at the feasibility of using optical gyros to support a guidance system for the Delta rocket which was the principle product of MDAC at my location at the time. The two possible alternatives were ring laser gyros and a new possibility the fiber optic gyro which has just been demonstrated by Vali and Shorthill. The basic problem was to determine if either of these approaches had any hope of becoming the next generation rotation sensor and if so what McDonnell Douglas should do about it. This lead to McDonnell Douglas assuming an early leadership role in fiber optic rotation sensors based on the Sagnac interferometer as well as spin off inventions associated with that effort. McDonnell Douglas inventions in this area were licensed to Blue Road Research, Blue Road Research inventions have been licensed to Columbia Gorge Research and the world of applications associated with the fiber optic Sagnac interferometer has in many ways been greatly expanded and at the same time there are areas that have barely been touched. It is my hope that this paper and perhaps more importantly the literature it refers to will help lead others down their own paths of exploration. The starting point will not be the same and the applications may have yet to be imagined but I am confident that many others will find a tour of the Sagnac interferometer an interesting journey.

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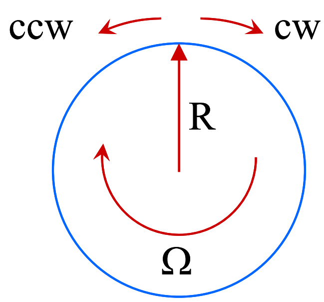
EARLY DAYS AT MCDONNELL DOUGLAS

It wasn't long after I started to look at rotation sensors that I had convinced myself that ring laser gyros were seriously difficult to make successfully. Their development had started about a year after the invention of the laser and the military and US Government had sunk hundreds of millions of dollars into their development. The motivation was that mechanical gyros involved spinning masses operating at high speed with ball bearings that tended to wear resulting in reliability problems that were a major cause of commercial and military aircraft being grounded as well as a serious safety concern. Fundamentally the aerospace industry and its military and commercial customers wanted this problem solved as quickly as possible and were willing to invest heavily to make sure it happened.

The basic Sagnac effect is illustrated by Figure 1. A light beam is split into clockwise (cw) and counterclockwise (ccw) light beams at a point on a closed path. To make things easy in the case of Figure 1 this is a circle. If the circle has a radius R and it rotates at a rate Ω in the clockwise direction then the light that propagates about the circle in the clockwise direction has to travel a bit further as the rotating circle moves away it while the counterclockwise rotation makes the path a little shorter as the circle moves in a direction opposite this light beam. The net result is a difference in path length between the two light beams due to rotation [1] and when the two light beams are combined a difference in the phase relationship due to rotation when they recombine.



$$\text{cw path: } 2\pi R + \Omega RL/c$$

$$\text{ccw path: } 2\pi R - \Omega RL/c$$

$$\text{Net path difference: } 2\Omega RL/c$$

$$Z_R = 2\Omega RL/(\lambda c)$$

Figure 1 The Sagnac effect generate a path difference between counter-propagating light beams about a closed path resulting in a relative fringe shift or phase difference.

In terms of the performance of the ring laser gyro, the Sagnac effect acts to lengthen or shorten the effective path of a laser beam propagating along a closed path. Usually this involves a laser cavity consisting of three or four high quality mirrors. Consider the case of the ring laser gyro illustrated schematically by Figure 2. In this case there are three mirrors. When the ring laser gyro assembly rotates clockwise the effective length of the optical cavity in this direction lengthens and to maintain a lasing condition the wavelength associated with that direction gets longer. In the counterclockwise (ccw) direction the light beam traverses a shorter path due to the clockwise (cw) rotation and the net result is a shorter lasing wavelength. By using a partially transparent mirror both light beams can be extracted and combined. Since they have slightly different lasing wavelengths their frequencies are different and a beat signal results whose frequency is proportional to rotation rate. Ideally this would be a linear relationship but at low rotation rates there is a small amount of backscatter from the mirrors and the gases associated with the lasing cavity that cause the two light beams to lock together in frequency resulting in no effective output for low rotation rates. Several methods were devised to circumvent this "lock in" region with the commercially successful approach involving a piezoelectric "shaker" that rotated the assembly cw and ccw quickly enough that the two counterpropagating light beams were unlocked and rotation could be sensed.

The time interval over which the two light beams were locked together is gated out and the average of the signals from the cw and ccw piezoelectric shaker motion is used to assess the rotation rate.

For some applications the piezoelectric shaker was a significant issues and the ultra high clean room conditions and unitized construction needed to make the ring laser gyro functional made fiber optic gyros an interesting candidate to supersede ring laser gyro technology.

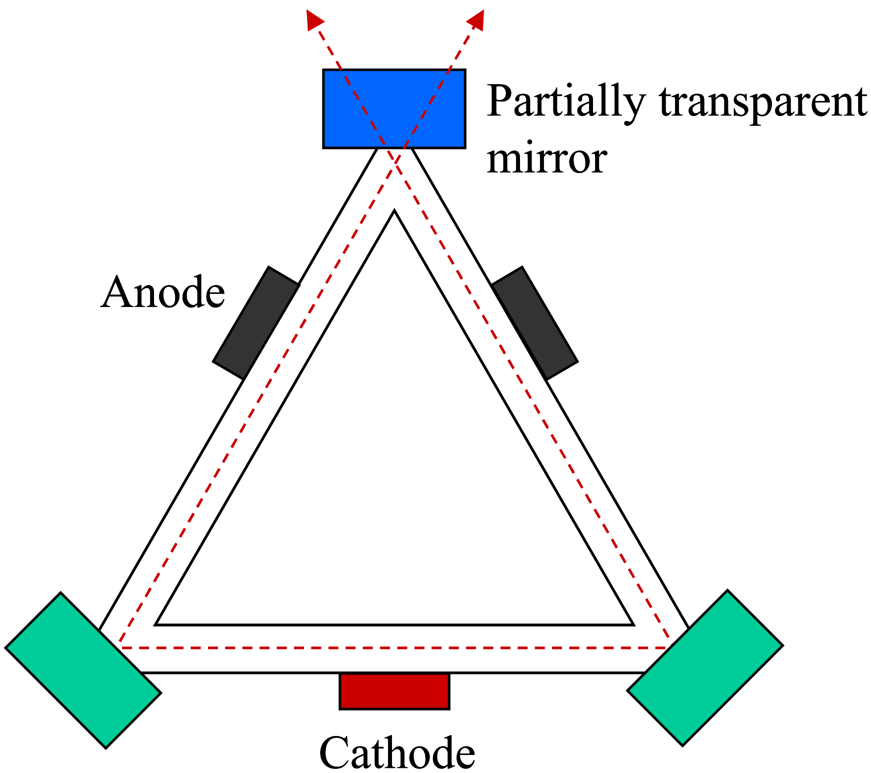
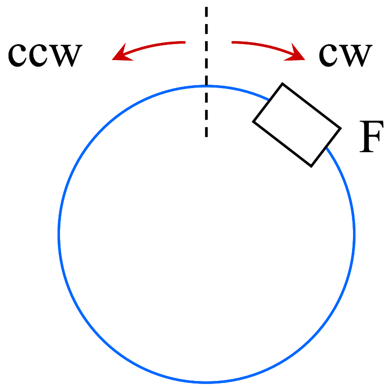


Figure 2 Ring laser gyro configuration consisting of three mirrors arranged in a symmetric configuration to avoid errors induced gas flow via electric current.

Vali and Shorthill at the University of Utah had in 1976 built a fiber optic gyro based on a helium neon light source. There were several major performance issues but the major one that concerned McDonnell Douglas management was that it was inherently nonlinear. That is with faster rotation rates the fiber optic gyro would move through a sinusoidal fringe. The ring laser gyro by comparison has a frequency output that was directly proportional to rotation rate.

My response to this was to start to think about ways to counterbalance the rotationally induced fringe shift with some "counterbalancing" mechanism. The original thought was to put a frequency shifter near one end of the fiber coil. Since optical fibers have dispersion with respect to wavelength and the frequency shifter would induce a wavelength shift in one direction versus the other one counterpropagating light beam would see a relative optical path length shift relative to the other one via this mechanism and the idea was to control the frequency to counterbalance the rotationally induced fringe shift. I brought this idea to Richard Cahill who I worked for and we started to work closely together on expanding and refining these ideas with the result being the "phase nulling optical gyro". The major mechanism for shifting phase is not dispersion. Figure 3 shows again an optical closed circuit with counterpropagating light beams originating from and optical light source. The cw beam passes through a frequency shifter before circulating around the loop and is shifted up by an incremental frequency F. The ccw light beam circulates through the loop without being frequency shifted until it exits. Both light beams are at the same frequency when they combine. The net result is that there is a fringe shift between the two that is given by FLn/c where L is the length of the loop, n is the index of refraction and c is the speed of light. Using this to offset the rotationally induced fringe shift renders $F=2\Omega R/\lambda n$ which is the fundamental equation for the closed loop fiber optic gyro and also incidentally the fundamental equation for the ring laser gyro.



$$Z_{Fcw} = (F_o+F)(Ln/c)$$

$$Z_{Fccw} = F_oLn/c$$

$$Z_F = FLn/c$$

Setting $Z_R = ZF$

Renders $F = 2R\Omega/\lambda n$

Figure 3 The closed loop (phase nulling) fiber optic gyro uses a frequency difference between counterpropagating light beams to counterbalance rotationally induced phase shifts.

Once these idea were worked out the next step was to build the first closed loop fiber gyro which is shown in Figure 4. It consists of a helium neon laser generating a light beam that is directed through bulk mirrors and a central beamsplitter to an acousto-optic modulator that acts as a frequency shifter and into one end of a 100 m length of single mode optical fiber cable. The other counterpropagating light beam is directed into the other end of the fiber optic coil. The whole assembly was about one meter square and 0.5 m high.

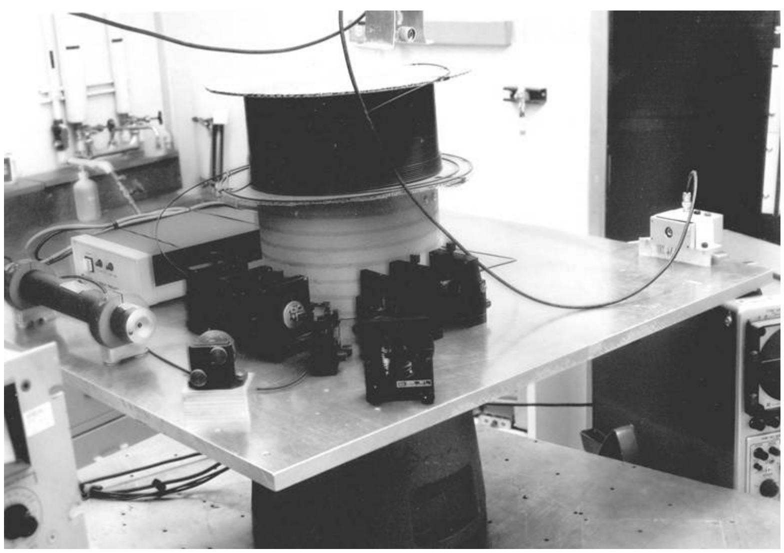


Figure 4 The first closed loop (phase nulling) fiber optic gyro (1978) used bulk optic components and was about one meter square.

The unit shown in Figure 4 did demonstrate the basic operating principles of the closed loop fiber optic gyro and operated from about 0.5 deg/sec to 30 deg/sec. Limited on the low end by noise and on the high end by paranoia associated with electrical cabling being wound faster than I would have liked.

In the process of looking for noise sources limiting the closed loop fiber gyro on the low end it became apparent that the Sagnac interferometer was a very good acoustic sensor. Our initial awareness of this came about as I and a few other people were watching the output of the interferometer and the noise went up and down. Our voices were inducing the noise and we proceeded to use a tuning fork to look more carefully at where the hot spots were. This was one of a series of derivative inventions associated with early work on the closed loop fiber optic gyro.

Unfortunately our sponsors (the Delta Rocket people) were not very impressed with the size of our demonstration and they wanted a 4 inch diameter closed loop fiber gyro as our next step. I lobbied for 6 inches and we wound up compromising at 5 inches (about 12.5 cm).

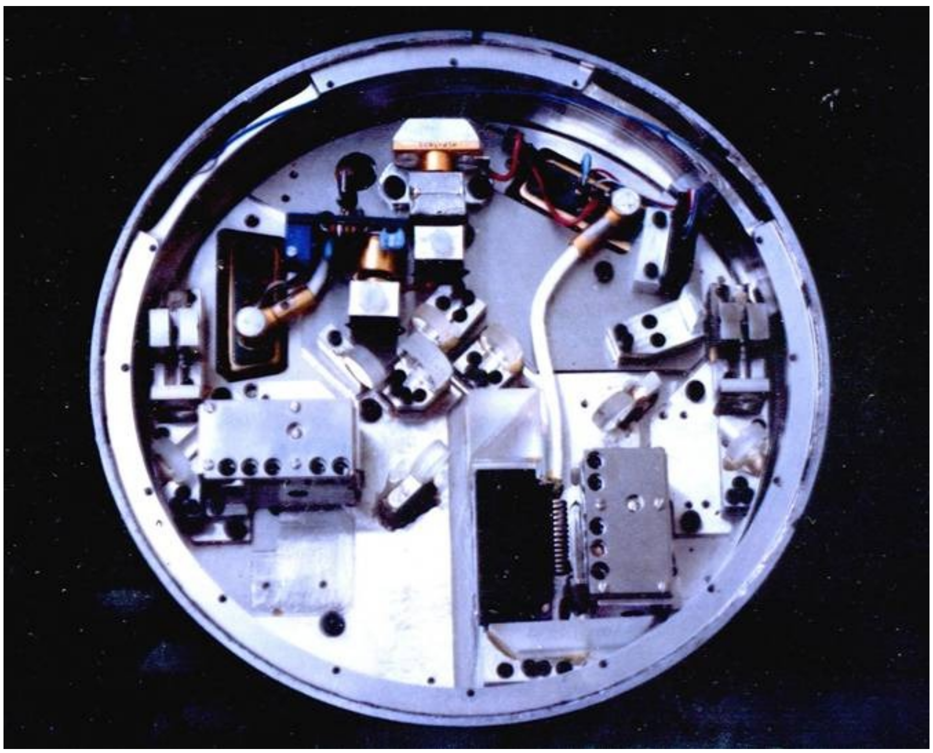


Figure 5 The first solid state closed loop (phase nulling) fiber optic gyro (1979) used bulk optic components and was about 12.5 cm in diameter and 2.5 cm high.

At this time there were very few laser diodes and a $3000 Hitachi laser diode was used as the light source. Miniature bulk optic mounts were designed along with angled end faces to avoid back reflections. To align the collimated light beams into the 4 micron core optical fiber (some of the original single mode optical fiber produced by Corning) a series of optical wedges in turn screw mounts were used. The assembly took some weeks of intensive effort and interestingly enough the laser diode which had survived the assembly process only lasted about one half hour during initial rotational testing. So instead of a laser diode as a light source we now had effectively a very expensive and low power light emitting diode. Much to my surprise the closed loop fiber gyro continued to work with approximately the same signal to noise ratio. The overall power was down dramatically but so was the noise floor that had been limited by coherent back scatter associated with the laser diode operation. The search was on for low cost, low coherence light sources!

Our internal sponsorship at McDonnell Douglas changed from the Delta Rocket people to those involved in tactical missiles who now wanted a much smaller closed loop fiber gyro which resulted in 1980 in a 6 cm diameter design shown in Figure 6 that was and still may be the smallest bulk optic solid state closed loop fiber gyro ever built. One interesting feature was that the coil was designed so that it could be place remotely from the bulk optic platform and used to measure very intense vibrations.

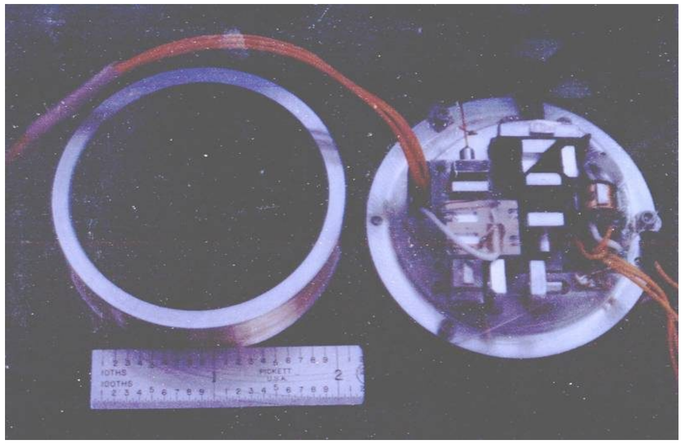


Figure 6 Possibly the smallest solid state closed loop (phase nulling) fiber optic gyro (1980) using bulk optic components that was ever built was approximately 6 cm in diameter.

By this time McDonnell Douglas had firmly established itself as a leader in the development of fiber optic gyros and had an expanding patent base for closed loop fiber optic gyros. It had also won every competitive US Air Force contract for fiber optic gyro development which lead to a series of prototype fiber optic gyros including the 1983 closed loop fiber gyros shown in Figure 7. These units had some of the first super radiant light sources ever made and featured some early versions of packaged fiber beamsplitters that were made by Gould and McDonnell Douglas to support fiber sensor programs that included acoustic sensors as well as fiber gyros.

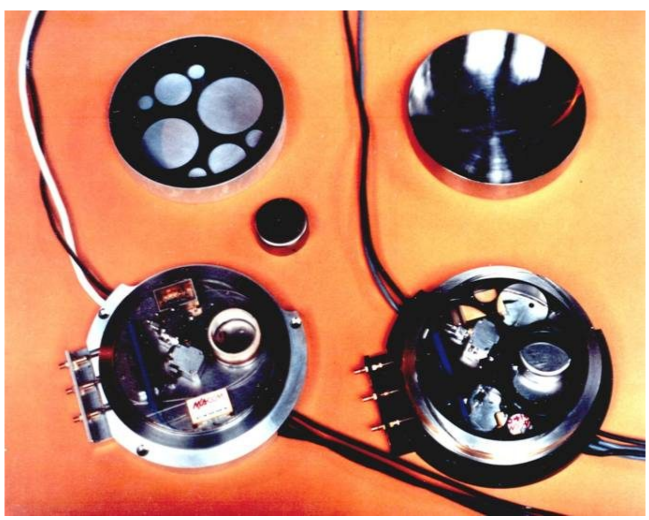


Figure 7 Early fiber optic gyro prototypes (1983) such as those shown in this figure (1983) were developed for the US Air Force with funding from Wright Patterson AFB and Eglin AFB.

In parallel with the development of fiber optic gyros for Air Force applications McDonnell Douglas received support for the development of the first oil fiber optic gyro to assist in gyro compassing in an oil field service tool. This unit consisted of oval fiber optic gyros that were inserted into a 5 cm tube approximately 3 m in length that was displayed at an oil drilling show in Houston in 1982.

By the 1985 time frame McDonnell Douglas was faced with a decision as to whether or not to produce fiber optic gyros. By this time other major supplies of rotation sensors to McDonnell Douglas were lobbying strongly for licenses on the closed loop fiber optic gyro. A plan was put in place and submitted to McDonnell Douglas management for development of production fiber optic gyros. It went to the highest levels of the company and second rounds of inputs were made after which the decision was made that the technology would be licensed. Over the next several years every major developer of closed loop fiber optic gyros in the United States, Europe and Japan was licensed.

This turn of events was a major disappointment; however McDonnell Douglas softened this by allowing internal development funding that had been directed toward fiber optic gyros to be turned toward derivative inventions involving the Sagnac interferometer and the emerging field of "fiber optic smart structures".

STRAIN, ACOUSTIC AND DISTRIBUTED SENSING

Three series of derivative inventions associated with the fiber optic gyro program at McDonnell Douglas involved strain, acoustic and distributed sensing. The strain sensors were a result of using acousto-optic modulators as frequency shifters to support closed loop fiber optic gyros. The acousto-optic modulators used had operational frequencies of 80 to 100 MHz which meant that if only one modulator was used the two counterpropagating light beams in the Sagnac loop had a large offset frequency. If the fiber changed length than there would be a fringe shift given by $F(Ln/c)$. This resulted in a strain sensitivity that was supported by the equation $dF/F=-dL/L$. So if frequency changes of approximately 1 Hz could be resolved (our closed loop fiber optic gyro electronics could fairly easily support this) then with an offset frequency of 100 MHz, changes in the length of the Sagnac loop of about 1 part in 10^8 could be measured. For a 100 m fiber coil this meant that changes of about 1 micron could be resolved. This type of Sagnac strain sensor was used to support early measurements of strain in composite materials with the first demonstrations taking place in about 1985 and this was the start of fiber optic smart structure efforts at McDonnell Douglas. In the late 1980s fiber grating sensor technology largely replaced the Sagnac interferometer for monitoring composite materials at McDonnell Douglas. The Sagnac interferometer based strain sensor did however have the very interesting property of being a long gauge length strain sensor. One potential application that was considered in the 1990s was to use this type of sensor to support measurements of displacements over large distances for such applications as earthquake monitoring. However the emergence of global positioning satellites and GPS technology enabled lower cost alternatives for the principal targeted applications.

The Sagnac acoustic sensor in addition to having high sensitivity had a number of other interesting properties including a position dependent response. In particular an acoustic wave at the center of the fiber loop would have virtually no effect because both counterpropagating light beams arrive at the same time. As the position of the acoustic wave moves toward the central beamsplitter the response increases linearly. This property enables these acoustic sensors to be used effectively in measuring the position as well as the amplitude of a time varying event. Figure 8 shows one of several versions of distributed sensors using the Sagnac interferometer. In this case two independent Sagnac interferometers are interlaced using wavelength division multiplexing elements. A simple method of doing this is to use 1300/1550 nm wavelength division multiplexing elements formed by biconical tapers similar to those employed for fiber beamsplitters. By using a 1300 nm light source and a 1550 nm light source two independent Sagnac loops can be created. The configuration shown in Figure 8 show that they share common lengths of fiber and since each has zero sensitivity to time varying events in the center of the loop and increasing sensitivity as the event moves toward the central beamsplitter of each loop, position can be determined by taking the ration of the signals from each loop and the amplitude may be measured by taking the sum.

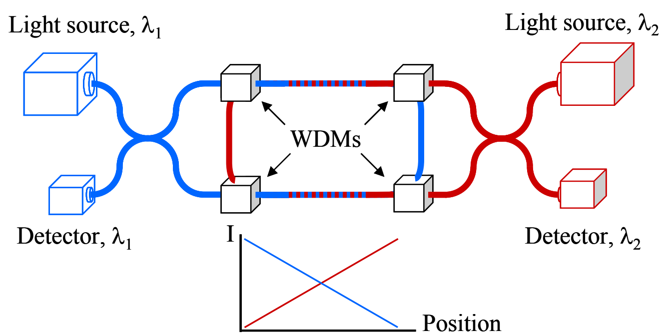


Figure 8 Sagnac distributed sensors for time varying events can be configured by interlacing two independent Sagnac interferometers using wavelength division multiplexing techniques.

SAGNAC SECURE FIBER OPTIC COMMUNICATION SYSTEM

Another example of a Sagnac interferometer application is the Sagnac secure fiber optic communication system that may be used to transmit data securing between two locations. In this case a high speed phase modulator that may be an intergrated optic modulator is used to impress information onto the system by inducing a phase difference between counterpropagating light beams. Since the Sagnac interferometer is inherently balanced when the two light beams come back together the phase difference causes the combined light beams to be directed either back to the light source or toward the detector dependent on their relative phase. Thus the central beamsplitter acts as a high speed switch and recreates the data stream. There are several way to appropriately format the data impressed by the phase modultor including bursting packets of information and continuously. The key point though is that the information flowing between the receiver (light source, central beamsplitter and detector at one location) and the transmitter (phase modulator offset from the center of the Sagnac loop) is impressed in phase. If a low coherence light source is used it is very difficult to extracts this phase information. A single point tap essentially sees what appears to be a defective fiber line with the light source on continually. This system was developed by McDonnell Douglas and approved for transmission of classified information by the NSA COMSEC commercial endorsement program and licensed by McDonnell Douglas.

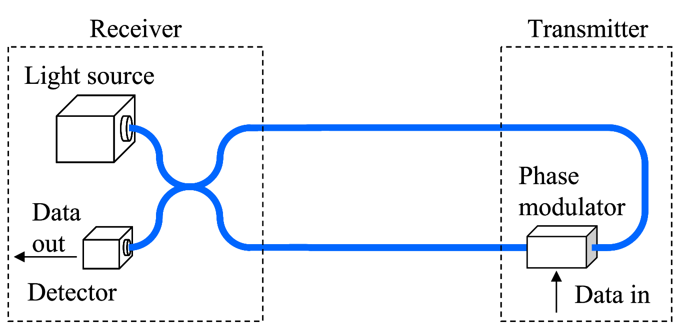


Figure 10 Sagnac secure fiber optic communication system that can be used to secure data transmission between two locations.

SUMMARY

The Sagnac interferometer has been used to support the development of the fiber optic gyro which remains one of the most successful and widely deployed fiber optic sensor technology. Many other forms of fiber optic sensors based on the Sagnac interferometer have been developed and used for such applications as strain, acoutic and distributed sensing as well as the field of secure fiber optic communication. These applications while less developed will likely become important for many future applications.

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