EVALUATION OF RING LASER AND FIBER OPTIC GYROSCOPE TECHNOLOGY

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Abstract

In past years much interest has been shown in the development of optical gyroscopes which offer the potential of solid state, highly reliable performance immune from many of the mechanical effects which restrict the performance of conventional spinning mass gyroscopes. Both ring laser and fiber optic gyros operate by sensing the difference in propagation time between beams of light traveling in clockwise and counter-clockwise directions about some closed optical path [1]. This paper presents a brief overview of optical gyroscopes and examines their suitability to a particular application where the current mechanical device has exhibited poor reliability. Conclusions are formulated that support the recommendation of developing an open loop, analog fiber optic gyroscope which will satisfy the requirements of the particular application of interest as well as those of similar systems.

With the advent of laser technology in the 1960's, a concentrated effort began to replace rotating mass gyros with devices utilizing circulating light. This effort resulted in the development of laser gyroscopes for certain high performance applications such as aircraft navigation. More recently, a parallel effort has emerged to develop fiber optics gyroscopes which can potentially be smaller, more rugged, and less costly than laser gyros.

Key words: Rotating mass gyros, fiber optic gyroscope, ring laser, laser gyros, open loop, circulating light.

Introduction

Historically, rate sensing requirements have been satisfied by conventional spinning mass gyroscopes whose operation depends on the angular momentum generated by a rotating wheel or ball. While modern gyroscopes are highly developed, sophisticated instruments, they are inherently sensitive to environmental conditions and are limited by a variety of mechanical effects.

The AN/AAS-35, Pave Panny system is a laser targeting system which incorporates a gimbal assembly to mount and position optical receiver components. The gimbal assembly contains two identical, single axis mechanical gyros. Pave Penny requirements are not particularly demanding from the perspective of gyroscope performance, but are extremely rigorous environmentally. The combination of relatively low performance specifications and harsh environment indicates that an optical gyro may be preferred over the current mechanical device.

The goal of this paper is to present the findings and recommendations developed during a feasibility study of upgrading the technology found in the AN/AAS-35, Pave Penny rate gyroscope.

Optical Gyroscope Technology

Ring laser and fiber optical gyros both operate by sensing the difference in propagation time between beams of light traveling in clockwise and counter-clockwise directions about some closed optical path. A rotationally induced variance in path length produces a phase difference between the light beams propagating in opposing directions. This difference is generally known as the Sagnac effect and forms the basic operating principle of all optical gyroscopes [2].

The techniques used to measure the Sagnac effect in ring laser devices are vastly different than those employed in fiber optic sensing. These differences serve as the distinction between the two classes of devices and determine their size, weight, power requirements, performance, and cost [3].

As illustrated in Figure 1, there are various classes of ring laser and fiber optic gyroscopes. Ring laser gyros are distinguished by the method employed to overcome or reduce the lock-in effects which occur at low rotational rates. Look-in is eliminated either by the introduction of a mechanical dither, magneto-optic biasing, or by the use of multiple optic frequencies. Fiber optic gyros are categorized by the techniques employed to measure the rotationally induced Sagnac effect. Interferometric fiber optic gyros (IFOG) use fringe pattern examination to sense the Sagnac effects while resonator fiber optic gyros (RFOG) employ resonant fiber cavities to do so.

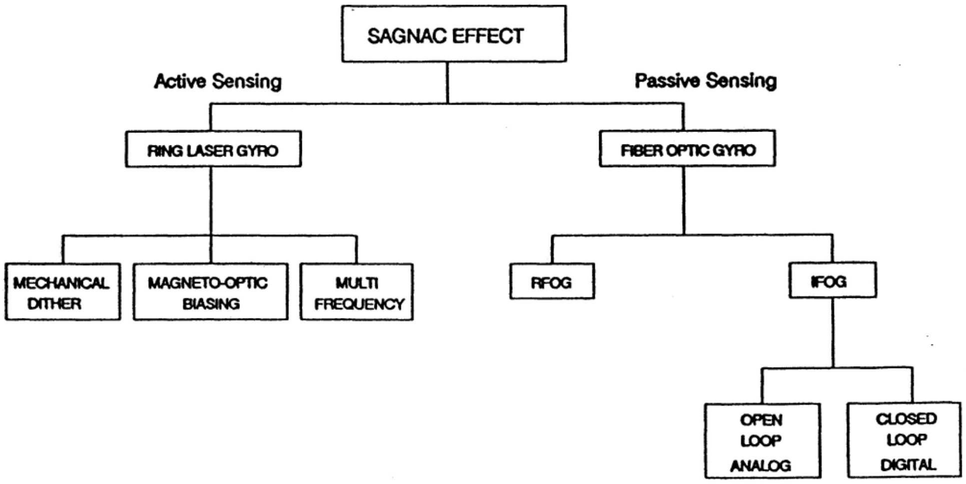


Figure 1. Optical gyroscopes [2]

Basic Theory of Ring Laser Gyros

Ring Laser Gyroscopes (RLG) combines the functions of optical frequency generation and rotation sensing into a laser oscillator within a ring shaped cavity. Typically, as in Figure 2, ring laser gyros consist of a solid block, either square of triangular, of glass ceramic material into which a lasing medium is introduced. The electrodes provide gain for the lasing medium, generally a helium/neon mixture due to its short coherent length and index of refraction of nearly 1.0, which generates two independent beams direction in opposite directions around the cavity. In order for the optical path to support lasing, there must be an integral number of wavelengths around the path and oscillation will occur at that frequency, f which meets this requirement. The cavity size is adjusted to support oscillation at frequencies optimal to the lasing media [4, 5].

This differential in frequency between the two traveling waves, the beat frequency Δf, is described in the following relationship:

$$\Delta f = \frac{4A\Omega}{\lambda_s P} \tag{1}$$

Where A is the area and p the perimeter of the ring cavity, λ_s is the wavelength of the light in the lasing medium and Ω is the angular rate of rotation.

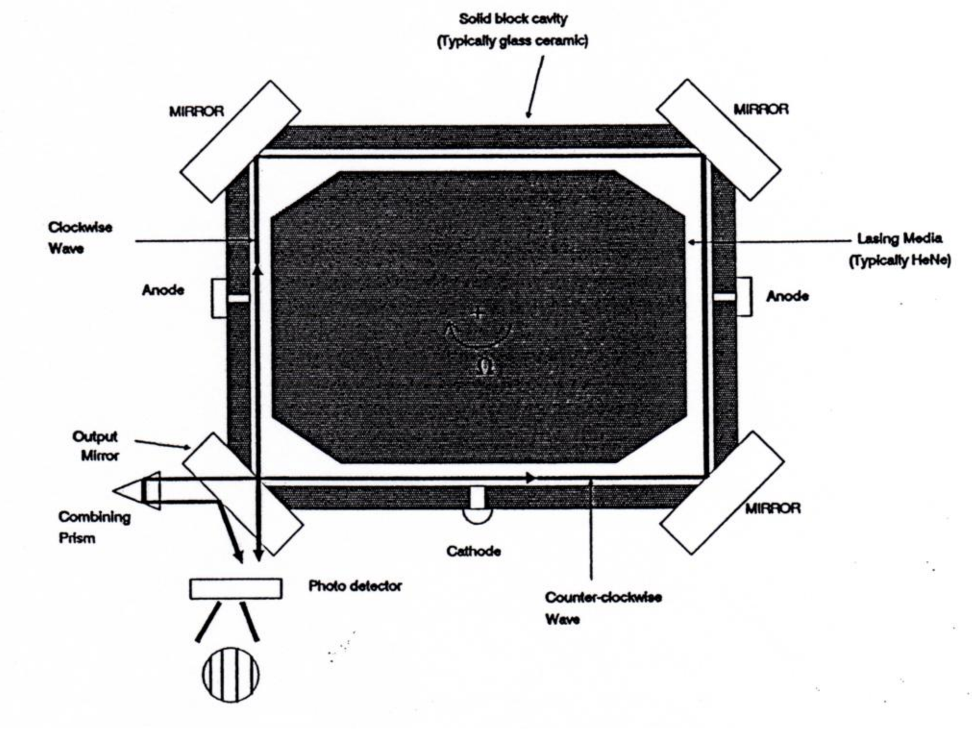


Figure 2. Typical ring laser gyro [4]

Here, the ratio $\frac{4A}{\lambda_s P}$ is known as the scale factor, K, of the gyro and Δf is directly proportional to the rate of rotation Ω.

The output of the ring laser gyroscope is typically developed by the use of a combining prism which produces two nearly collinear beams interfering to create fringe patterns sensed by the photo detectors [6]. The number of beats during a time interval is directly proportional to the rotation rate and the direction of fringe movement is indicative of rotational direction. In practice, the ring laser gyro is often operated in an integrating mode where each cycle of the beat frequency is counted as one unit of angular displacement.

Limitations of Ring Laser Gyros

The ring laser gyroscope today is well established in the medium and high performance markets. It offers many advantages over mechanical gyros; digital output linear with angular rotation, high sensitivity and stability, quick reaction times, insensitivity to acceleration and immunity to most environmental effects [7]. In spite of these advantages, the RLG remains a specialized instrument whose utility varies with the application and several factors limit its selection over modern mechanical system. The exacting cavity geometries and precision mirrors required for RLG construction and the necessity of assembly under stringent clean room conditions drive its cost beyond economic application to low performance system.

The size and weight of the RLG are other limiting factors to its use. The solid glass optical block and mechanical dither assembly found in most RLGs unavoidably add to their weight [8].
Attempts to miniaturize the RLG have been met with a corresponding decrease in their reliability. While large ring laser gyroscopes have demonstrated over 10,000 hours of operation, smaller units (a few cm diameters) are limited to a few hundred hours of use. Additionally slow leakage of the gas media, insignificant in large systems, may lead to shelf life problems in smaller RLGs.
The power requirements of RLGs are high. To support the lasing action on which RLGs depend, power sources capable of delivering several hundred volts, at low current, are required. Typical RLG power requirements are five to ten watts [9].

Basic Theory of Fiber Optic Gyros

There are currently two main classes of fiber optic gyres under development, the interferometric fiber optic gyro (IFOG) and the resonant fiber optic gyro (RFOG). The latter of these, the RFOG, has received less attention to date and, though it appears to offer better potential accuracy, is the less mature technology [10]. RFOG devices closely resemble ring laser gyros. They require a narrowband light source and rely on an optical cavity. The cavity is formed from optical fiber tuned so that only one frequency of light will propagate. Applied rotations change the wavelength and hence the frequency of the light which will propagate. The basic configuration is illustrated in Figure 3.

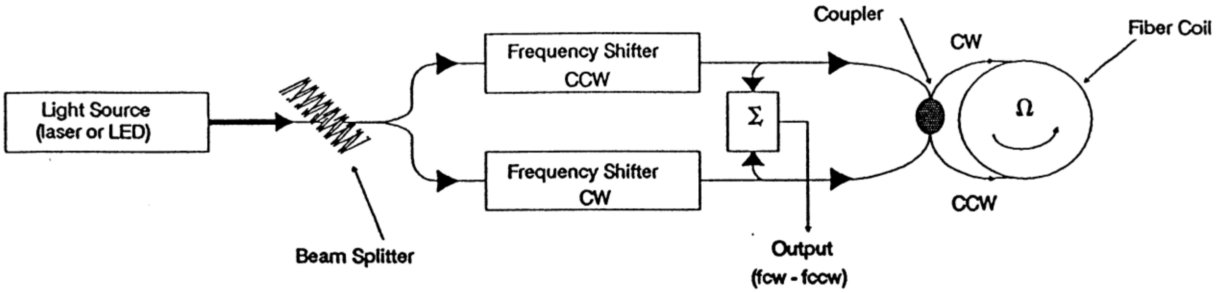


Figure 3. Resonant fiber optic gyro [10]

The fiber resonator is formed from a few coils of fiber and beam splitter. Two input ports accommodate the CW and CCW beams which are generally produced from the same coherent light source. In the absence of rotation, the two contra-rotating beams experience the same transfer function through the coil. When a rotation is applied, the optical path for one beam becomes slightly longer while that of the opposing beam becomes shorter producing Sagnac frequency shifts.

As in RLGs, the resonant fiber optic gyro senses the beat frequency:

$$\Delta f = f_{cw} - f_{ccw} \tag{2}$$

Unlike the ring laser gyro, RFOGs do not contain a lasing media within the resonator and therefore no direct measurement of Δf is possible; it must be measured by some means outside the resonant cavity. This is typically accomplished by the use of frequency shifting devices such as acousto-optic modulators (AOM) which track the beam frequencies, f_{cw} and f_{ccw}. The output is then developed by deriving the difference frequency as depicted in Figure 3.

A typical IFOG device is shown in Figure 4. The IFOG uses a low coherence, super-radiant diode as the light source and the polarizer, couplers, and sensing coil are generally fabricated from polarization maintaining fiber [11]. The phase modulator is a piezoelectric fiber stretcher consisting of a few turns of fiber wrapped around a piezoelectric transducer (PZT) cylinder.

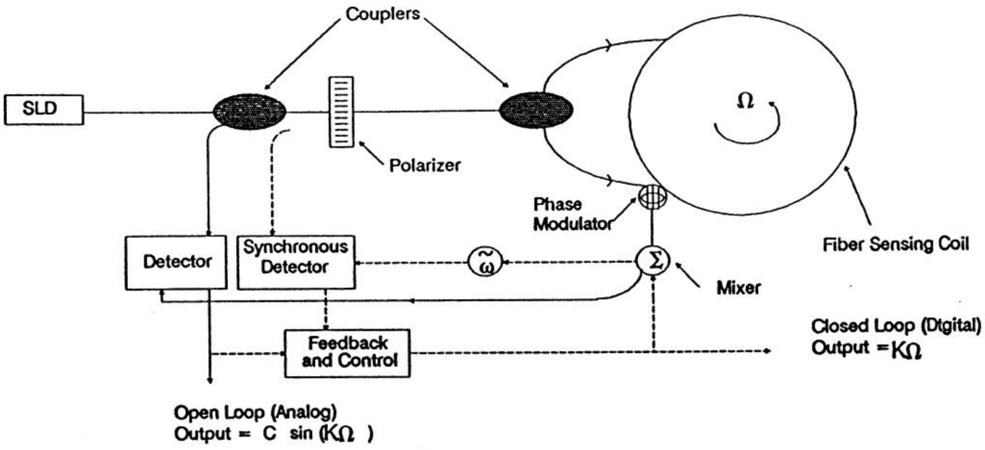


Figure 4. Interferometric fiber optic gyroscope [11]

Limitations of Fiber Optic Gyroscopes

Resonant fiber optic gyros, RFOGs, rely on key components (coherent light source, extremely low loss couplers, and frequency shifters) that are not readily available commercially and would likely not withstand harsh field environments. Backscattering caused by the optical components and the fiber itself tend to introduce undesirable nonlinear effects in FOG devices. This problem is readily overcome by using broadband light sources whose short coherent length reduces parasitic portions of backscattered waves. Fiber cable experiences time dependent fluctuations in reciprocosity due to stress, vibration, temperature or exposure to magnetic fields. This source of nonlinearity in FOGs is reduced by isolating the sensing coil from these disturbances and by special coil winding techniques and careful thermal design. In spite of these difficulties, FOGs have emerged as viable rate sensors for the low to medium performance ranges. For many applications, FOGs offer a solid state, low cost, highly reliable, lightweight alternative requiring low power, and no warm up time. Additionally, FOGs are capable of great flexibility in geometry and packaging [12].

Technology Comparisons

All optical gyroscopes operate by sensing and measuring the Sagnac frequency shifts induced by rotation. The means by which this is accomplished are vastly different and determine the performance, cost, design constraints, and appropriate areas of application for each type. Table 1 illustrates typical gyroscope applications and associated performance requirements.

Table 1.Gyroscope applications and associated performance requirements

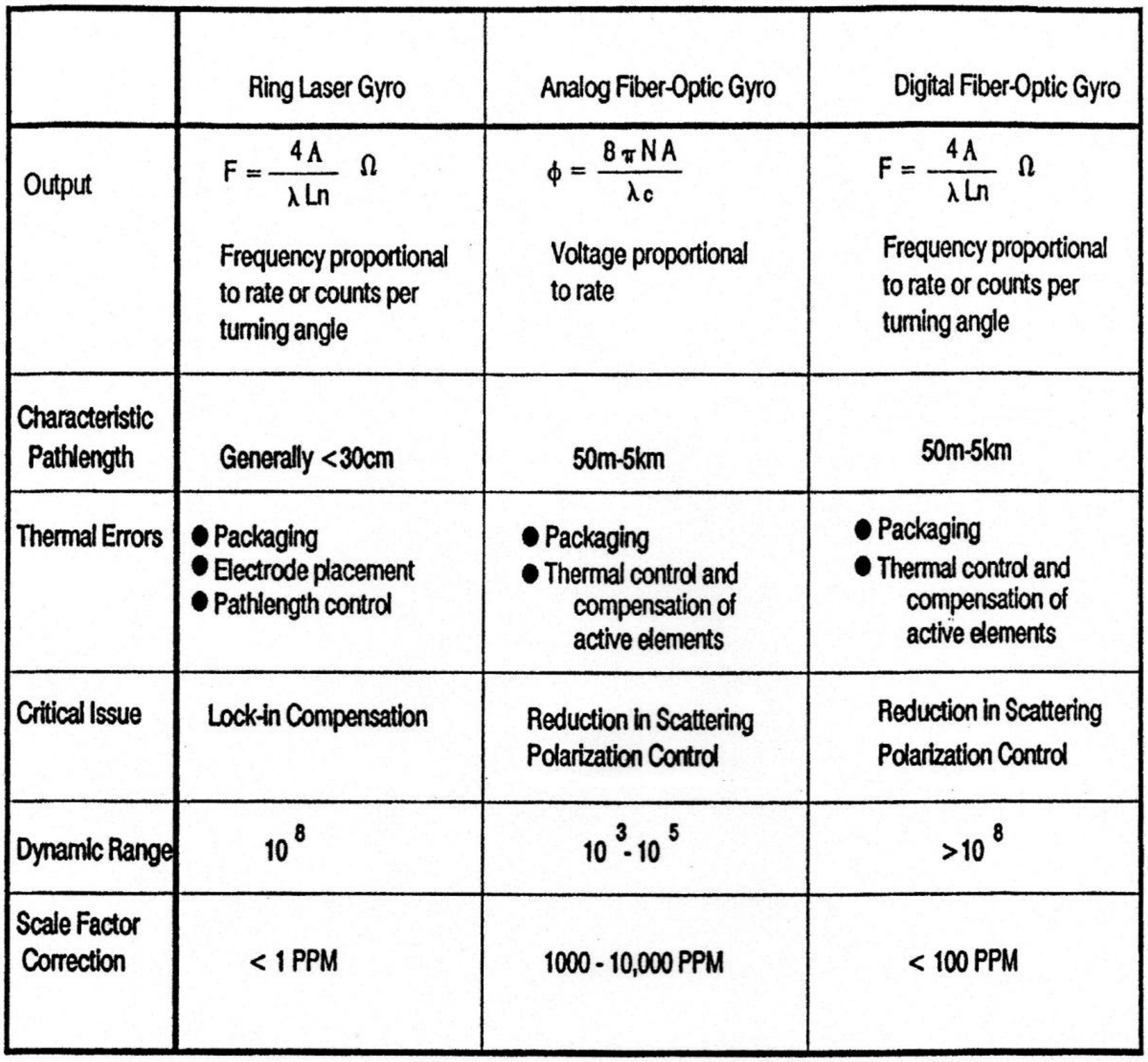
Type	Full Scale (deg/sec)	Scale Factor Stability (ppm)	Bias Stability (deg/hr)	Warm up Time (sec)	Cost	Size	Life (yr)
Aircraft Navigation	**100**	**25**	**0.01**	**>300**	**High**	**Not Critical**	**>1**
Space Booster	**10-30**	**50**	**0.1**	**>300**	**Medium**	**Not Critical**	**>1**
Air-To-Ground Spacecraft	**10**	**˜50**	**0.1-0.001**	**>300**	**High**	**Med-Small**	**>1**
Torpedo	**400**	**100-500**	**10-100**	——	**Low**	**Med-Small**	**3-5**
Air-To-Ground Tactical Missile Terminal Aided	**100-200**	**500**	**0.1**	**60**	**Very Low**	**Small**	**3-5**
Radar Guided Ground-To-Air Missile	**200-500**	**>1,000**	**10-50**	**1/4-10**	**Low-Med**	**Small**	**5-10**
Cannon Launched	**>500**	——	——	——	**Very Low**	**Small**	——
Pave Penny	**40**	**10,000**	**Approx. 1,000**	**30**	**Very Low**	**Critically Small**	**2,000 hrs**

As demonstrated in Table 1, Pave Penny requirements are rather undemanding in terms of bias stability and scale factor stability.

Performance Comparisons

Ring laser gyros and mechanical devices continue to dominate the high performance markets, bias stability of 0.01 degrees per hour or better, which currently remain out of reach for fiber optic gyros. This, however, leaves a very wide range of non-inertial grade application suitable for fiber optic devices. Various performance characteristics of optical gyroscopes are shown in Table 2.

Table 2. Performance characteristics of optic gyroscopes [9]



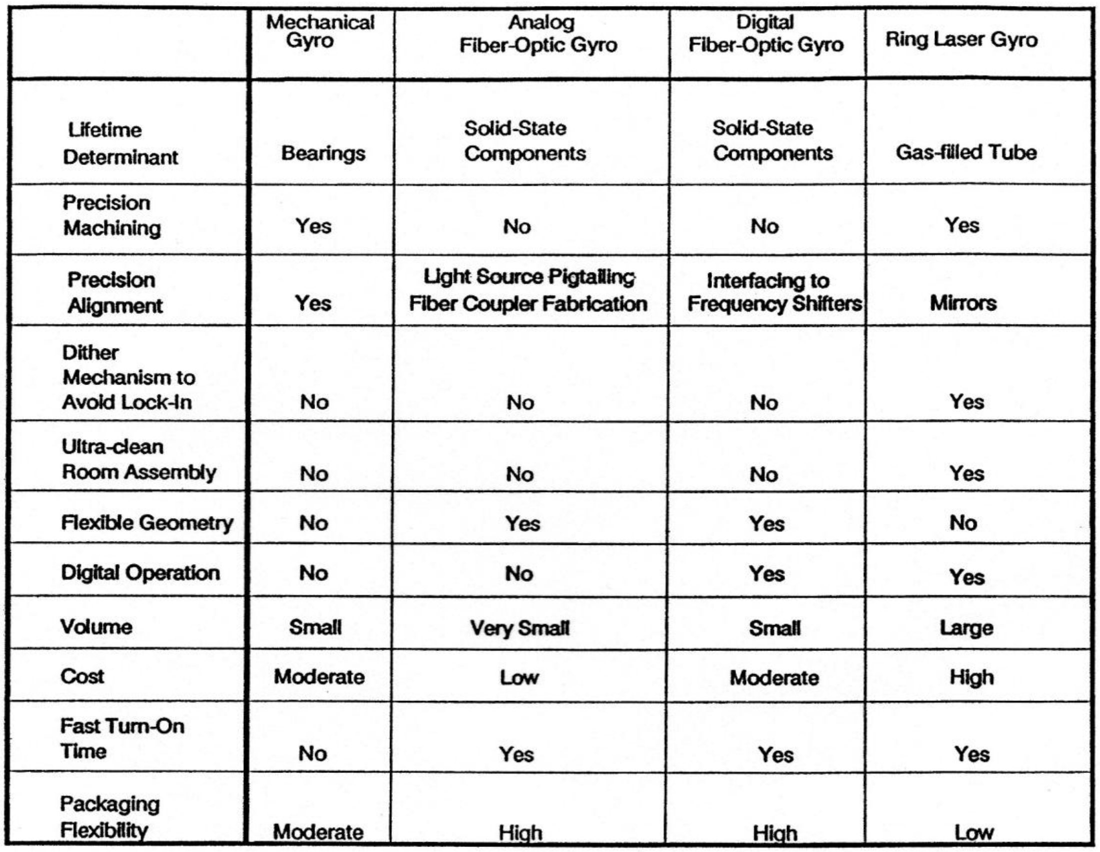
	Ring Laser Gyro	Analog Fiber-Optic Gyro	Digital Fiber-Optic Gyro
Output	$F = \frac{4A}{\lambda L n} \Omega$ Frequency proportional to rate or counts per turning angle	$\phi = \frac{8 \pi N A}{\lambda c}$ Voltage proportional to rate	$F = \frac{4A}{\lambda L n} \Omega$ Frequency proportional to rate or counts per turning angle
Characteristic Pathlength	Generally <30cm	50m-5km	50m-5km
Thermal Errors	● Packaging ● Electrode placement ● Pathlength control	● Packaging ● Thermal control and compensation of active elements	● Packaging ● Thermal control and compensation of active elements
Critical Issue	Lock-in Compensation	Reduction in Scattering Polarization Control	Reduction in Scattering Polarization Control
Dynamic Range	10^8	$10^3 - 10^5$	$>10^8$
Scale Factor Correction	< 1 PPM	1000 - 10,000 PPM	< 100 PPM

Fabrication and Packaging Comparisons

Ring laser gyros require exacting cavity geometries involving strict dimensional accuracy, precision mirrors, and extensive alignment and focusing. Their fabrication requires submicron machining and assembly under ultra-clean room conditions.

Fiber optic gyros are much less demanding in their fabrication techniques and much more flexible in their design and packaging. Mass production of fiber components, primarily for the telecommunications industry, has lead to a significant cost advantage over ring laser and mechanical gyros in many applications. Table 3 summarizes some of the major characteristics of mechanical and optical gyroscopes.

Table 3. Major characteristics of mechanical and optical gyroscopes



	Mechanical Gyro	Analog Fiber-Optic Gyro	Digital Fiber-Optic Gyro	Ring Laser Gyro
Lifetime Determinant	Bearings	Solid-State Components	Solid-State Components	Gas-filled Tube
Precision Machining	Yes	No	No	Yes
Precision Alignment	Yes	Light Source Pigtailing Fiber Coupler Fabrication	Interfacing to Frequency Shifters	Mirrors
Dither Mechanism to Avoid Lock-In	No	No	No	Yes
Ultra-clean Room Assembly	No	No	No	Yes
Flexible Geometry	No	Yes	Yes	No
Digital Operation	No	No	Yes	Yes
Volume	Small	Very Small	Small	Large
Cost	Moderate	Low	Moderate	High
Fast Turn-On Time	No	Yes	Yes	Yes
Packaging Flexibility	Moderate	High	High	Low

Conclusions

The application of an advanced technology rotation sensor to the AN/AAS-35 Pave Penny system is feasible. The low gyro performance required can be met by either a ring laser or fiber optic device. However, there are no existing products which can fulfill the requirement of a form, fit, and function replacement. The development of a Pave Penny gyro would primarily be an exercise in packaging. The requirement for a device meeting all form, fit, and function requirements of the current mechanical device and the inability to impose system level modifications of any kind heavily weight the decision in favor of a fiber optic device.

Both ring laser and fiber optic gyroscopes have exhibited the ability to perform under adverse environmental conditions where mechanical devices would be hard pressed to operate. Both have proven to be viable contenders to mechanical systems and continue to make inroads into what were once exclusive domains of mechanical devices. While ring laser gyros exist with performance specifications far in excess of Pave Penny requirements, their relatively high voltage requirements and high cost render them inappropriate for Pave Penny and similar applications. RLGs are sophisticated, expensive instruments developed for high end gyroscope applications and their development has not been, and likely will never be, aimed at low end applications such as Pave Penny. It can be concluded that:

1. Pave Panny requirements do not represent a challenge in terms of gyroscope performance. Instead, they are an exercise in packaging and environmental hardening.
2. Both ring laser and fiber optic devices are available which easily meet Pave Penny performance specifications, however, no products are currently available which comply with the form, fit and function restrictions.
3. It is feasible to develop an optical gyro for Pave Penny and similar systems. The necessary technologies have matured to the point where a solid state rate sensing gyroscope for such applications is within reach.
4. The preferred device for Pave Penny application is a fiber optic gyroscope due to its simple construction, lower cost, and greater packaging flexibility.

A low cost, solid state, fiber optic gyroscope which will meet Pave Penny requirements and, with minor modifications, can be made to satisfy rate sensing requirements in many other systems, across USAF and DOD inventories should be developed.

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