DESIGN AND DEVELOPMENT OF
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Preface

In the early years of aviation, guidance was provided by mechanical gyros based on spinning wheels or disks. According to the conservation of angular momentum, the orientation of the spinning object axis is unaffected by tilting or rotation of the support on which the spinning object is mounted. The spinning top therefore defines a direction in space that is used as a reference. By the end of the 1930s, the performance of mechanical gyros had improved considerably, and their use was widespread in commercial and military aircraft. World War II resulted in the mass production of mechanical gyros on an unprecedented scale, with increased accuracy and resolution. In subsequent years, the boom in commercial air travel and military requirements for improved aviation significantly expanded the marketplace for inertial navigation systems based on these gyroscopes.

The implementation of navigation systems for aerospace platforms remained an important issue as mechanical gyros were responsible for nearly 50% of aircraft departure delays. Thus, the demonstration of the ring laser gyro shortly after the invention of the laser became an area of extreme interest for both military and commercial aviation. The US Department of Defense spent hundreds of millions of dollars to support research and development, followed by funds to support the establishment of manufacturing lines at US companies in the 1960s and 1970s. These efforts led to the introduction of ring laser gyro systems onto military and commercial aerospace platforms in the late 1970 and early 1980s.

In the 1970s, the fabrication of the first low-loss single-mode optical fiber occurred at Corning. Shortly thereafter, Dr. Victor Vali and Professor Richard Shorthill at the University of Utah constructed and operated the first open-loop fiber optic gyro. Their idea was simple: construct a Sagnac interferometer with a multi-turn fiber coil, which increases the total area subtended by the coil in proportion to the number of turns and enhances the Sagnac phase shift by the same ratio. This opened up the possibility of moving away from the severe requirement associated with manufacturing ring laser gyros in ultra-clean environments with ultra-pure gases, very-low-expansion-coefficient ceramics, and very-low-backscatter mirrors.

An immediate issue with the fiber optic gyro involved the need for eight orders of magnitude of dynamic range for the navigation of aircraft and extreme linearity. The open-loop fiber optic gyro at the time seemed capable of a dynamic range of three or four orders of magnitude with sufficient levels of linearity. The solution introduced by Cahill and Udd at McDonnell Douglas Astronautics Company used a closed-loop fiber gyro approach that solved in principle the dynamic range and linearity issue with performance and underlying equations similar to those of the ring laser gyro. Like in other closed-loop systems, the output signal of the gyro, which is proportional to the rotation rate, is fed back to the phase modulator in the Sagnac loop in order to cancel the output signal. The readout of the gyro is then the feedback voltage applied to the modulator, which is also proportional to the rotation rate. The benefits of the closed-loop gyro stem from the fact that the output always equals or is very near zero, no matter how large the rotation rate is, up to a very large value imposed mostly by the large voltage dynamic range of the feedback circuit. The dynamic range is therefore greatly increased, and its linearity is excellent because the signal never deviates far from zero. This solution offered the potential for an all-solid-state rotation sensor with a lower overall cost.

Realizing the potential of the fiber optic gyro, like the ring laser gyro, has been a long and expensive process. Many researchers have made important enabling contributions, and many more engineers have worked diligently for many years on solving the problems associated with realizing viable inertial navigation and guidance at affordable costs. This book contains contributions from key engineers and scientists who have worked from as early as 1977 to the present on manufacturing high-performance fiber gyros for many applications.

In this book, Eric Udd provides a chapter that overviews early work on developing open-loop and closed-loop fiber gyros at McDonnell Douglas. These efforts resulted in the first solid-state fiber optic gyros and were highly directed toward demonstrating feasibility for a range of aerospace and oil and gas applications. In parallel, Professor John Shaw at Stanford University obtained funding from Litton Guidance and Control that fueled many successful years of research to improve the performance of fiber optic gyros. In particular, his research group pioneered a series of novel all-fiber components in its early years—especially fiber couplers with extremely low loss and backscattering, and a fiber polarizer with an exceedingly high extinction ratio—that were implemented to eliminate the bulk components used in McDonnell Douglas early prototypes and produced gyros with record-breaking rotation sensitivities. Many of Professor Shaw's graduate students went on to make major contributions to fiber optic gyro technology, including Hervé Arditty and Hervé Lefèvre (at Thomson CSF, then Photonetics, and now IxBlue), George Pavlath (at Litton Guidance and Control, now

Northrop Grumman), Ralph Bergh (who has founded and operated a series of companies supporting fiber gyros), and Michel Digonnet, who succeeded Professor Shaw at the Edward L. Ginzton Laboratory at Stanford.

Several people from the Stanford group have contributed chapters to this book. Hervé Lefèvre provides a "potpourri of fortunate events" that serves as a broad overview of the history and fundamental physics of the fiber optic gyroscope, and the events that turned out just right for fiber optic gyros. With Hervé Arditty, Hervé Lefèvre promoted the "minimum configuration" fiber optic gyro, i.e., the configuration that comprises the minimum number of components required to enforce reciprocity, a key property that was ultimately instrumental in the remarkable overall performance of the fiber optic gyroscope. These components were eventually implemented in an integrated-optic chip fabricated in lithium niobate, a technology that was also critical to the gyroscope's success. These insights, as well as the early development of effective phase modulation techniques, were among the key contributions they both made to fiber optic gyro technology. George Pavlath of Northrop Grumman overviews the state of the art of closed-loop fiber optic gyros and their applications. In the early 1980s, Litton Guidance and Control selected him to lead their fiber optic gyro program, and over the decades he has guided that group to many important achievements, including the implementation of fiber optic gyros on major aerospace platforms. Most notably, Litton Guidance and Control provided the compact closed-loop fiber gyros that navigated all of the Mars rovers, including Spirit, Opportunity, and Curiosity. Pavlath's chapter outlines the achievements of Litton Guidance and Control and Northrop Grumman. Ralph Bergh's chapter outlines a recently improved signal-processing approach for optimizing the closed-loop fiber gyro operation. The work at the Edward L. Ginzton Laboratory that Professor Shaw started continues under the direction of Professor Michel Digonnet. The chapter by Digonnet and his former graduate student Dr. Jacob Chamoun describes some of the latest efforts toward interrogating the fiber gyro with a coherent light source, instead of the conventional broadband light source, in order to produce the next generation of fiber gyros with improved scale-factor stability and reduced noise.

In the late 1970s, Professor Shaoul Ezekial at MIT demonstrated a different type of optical rotation sensor: the passive ring resonator. With James Davies, he later independently demonstrated a closed-loop fiber optic gyro similar to that of McDonnell Douglas. One of his students, Glen Sanders, joined Honeywell in Minneapolis in 1983. Honeywell was a leader in ring laser gyros but initiated research efforts in fiber optic gyros and resonant fiber optic gyros in the mid-1980s. This position increased in October 1986 when Honeywell acquired Sperry and their active fiber gyro program in Phoenix. Glen Sanders joined the Phoenix group in the late 1980s and became a leader of the fiber gyro program there. He was joined by key co-developer

Lee Strandjord and, later, by Steve Sanders in 1998. They continued to develop fiber optic gyros, particularly for high-performance applications, and they have demonstrated state-of-the-art approaches in RFOGs. They, and other Honeywell co-authors, summarize the history and status of this work in their chapter.

Also in the early 1980s, Richard Dyott of Andrew Corporation led his group in developing D-shaped optical fiber with an elliptical core. The D shape enabled the fabrication of fiber polarizers and polarization-preserving optical fibers. Andrew Corporation made satellite dishes, and their focus was on stabilizing these units. KVH Industries, Inc. acquired the fiber gyro capabilities of Andrew Corporation and improved the linearity and range of the open-loop fiber gyro. The result has been successful at producing units for the middle range of the rotation sensor market. Jay Napoli of KVH outlines the state of the art of these developments in his chapter.

Other companies continue to enter the fiber gyro marketplace as key patents have expired and new methods for enhanced performance are developed. The chapter by Al Cielo Inertial Solutions, Ltd provides an example of this type of company.

One of the keys to success of the fiber optic gyro are components and associated packaging that meet stringent requirements to reduce error sources. Examples of these components include polarization-maintaining optical fiber with thin coatings suitable for winding, polarizing optical fiber packaged for maximum and stable extinction ratios, and fiber couplers. Overall, the properties of polarization-maintaining fibers, fiber polarizers, and fiber couplers have enabled reductions in the fiber gyro bias drift by many orders of magnitude. Chris Emslie describes the specialty optical fibers and components that have played a significant role in fiber gyro development, and offers examples produced by the University of Southampton, Fibercore, and other key players.

In a fiber optic gyro, the configuration and packaging of the fiber coil is particularly important to reduce the errors induced by temperature variations, acoustic waves, and strains, as required to achieve high performance. Steve Yao at General Photonics offers a close look at quadrupole fiber-coil windings and the associated test procedures that are used to meet this goal.

The last chapter of the book is a personal history of the fiber gyro by Eric Udd. It provides a glimpse of some of the motivations, events, and people associated with the fiber gyro development and its introduction as an important product for many applications from 1977 to the present.

This book arose from efforts to form a special session to commemorate the 40th anniversary of the first hardware demonstration of the fiber gyro in 1976 by Vali and Shorthill. The invited expert papers published in the conference proceedings were extended and new material added in an effort to present both a historical perspective and a more in-depth representation of the existing state of the art. New chapters were prepared that extend the range of topics covered. We would like to thank the contributors to this book for their efforts over more than four decades to convert the dream of high-performance solid-state rotation sensors into reality.

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