1

THE EMERGENCE OF FIBER OPTIC SENSOR TECHNOLOGY

Eric Udd
Columbia Gorge Research, Fairview, Oregon

Telecommunications have been revolutionized by fiber optic technology. The revolution began with limited system applications needing superior performance provided by fiber optics. The revolution became a rout as mass production techniques coupled with technical improvements resulted in superior performance at lower cost than those of alternative approaches. Simultaneous improvements and cost reductions in optoelectronic components in combination with mass commercial production led to similar displacements and the emergence of new product areas, including compact disc players, personal copiers, and laser printers. A third revolution is emerging as designers combine the product outgrowths of fiber optic telecommunications with optoelectronic devices to create fiber optic sensors.

The areas of opportunity are staggering and include the potential of replacing the many of the environmental sensors in existence today as well as opening up entirely new markets where sensors with comparable capability do not exist. Figures 1.1–1.3 provide an overview of the types of fiber optic sensors that are being developed and the environmental parameters that are most often associated with each type of sensor. The chapters of this book that correspond to each of the sensors are also indicated. Figure 1.1 lays out the various types of extrinsic or hybrid fiber optic sensors. Extrinsic fiber optic sensors are distinguished by the characteristic that sensing takes place in a region outside the fiber. Hybrid fiber optic sensors are similar and can be thought of as a "black box" sensor for which fibers are used to carry light to the box and data

Fiber Optic Sensors: An Introduction for Engineers and Scientists, Second Edition.
Edited by Eric Udd and William B. Spillman.

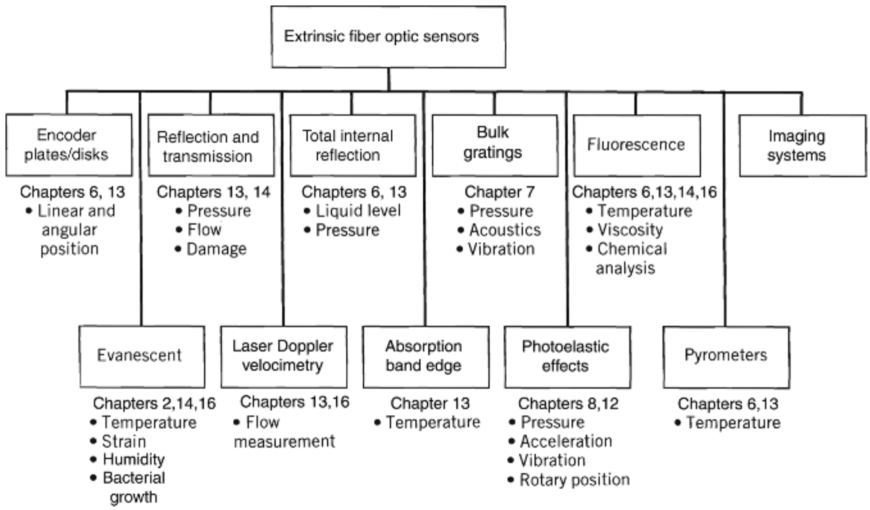

Figure 1.1 Extrinsic or hybrid fiber optic sensors: light transmits into and out of the fiber to reach the sensing region.

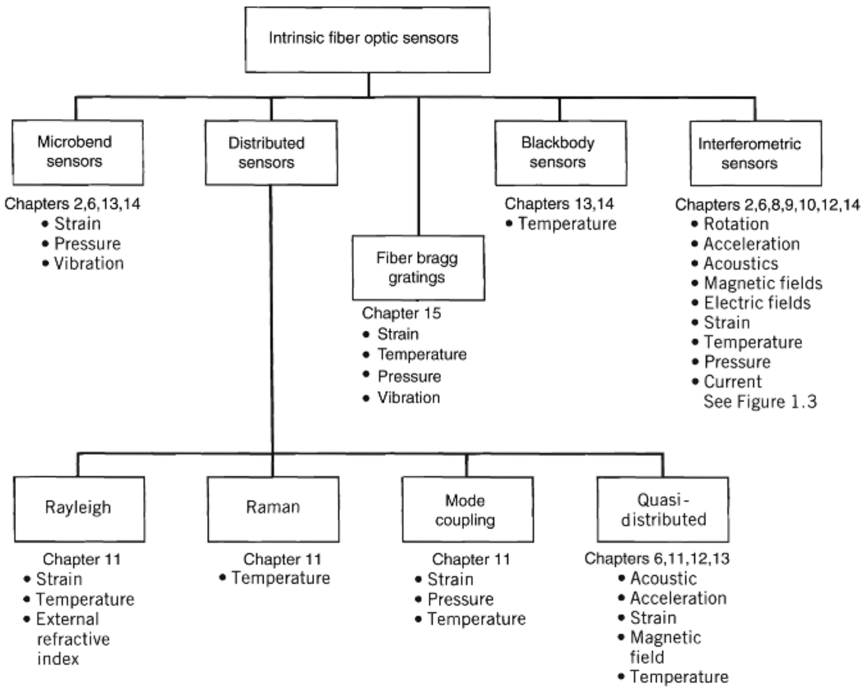

Figure 1.2 Intrinsic or all-fiber fiber optic sensors: the environmental effect is converted to a light signal within the fiber.

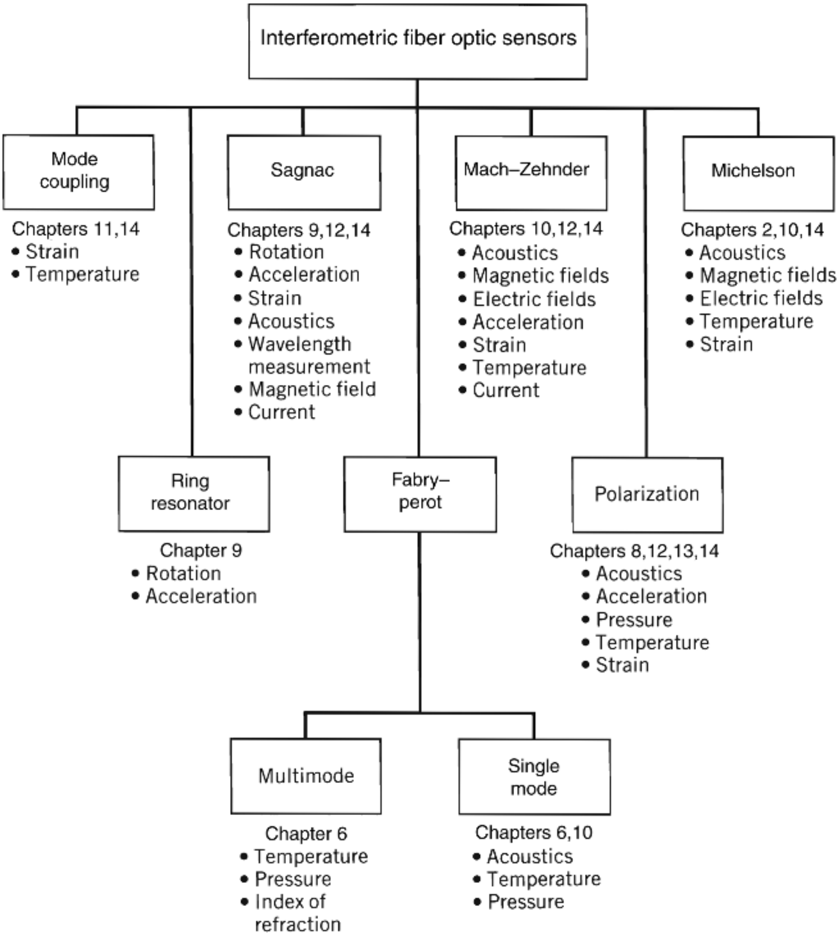

Figure 1.3 Interferometeric fiber sensors.

back. For most cases, the two terms can be applied interchangeably. A major distinction arises for the case of power by light sensors when a light beam is used to power an electronic sensor and data are carried back via a fiber optic data link. In this case, the hybrid designation would appear to be more appropriate.

Figure 1.2 shows a diagram illustrating many of the intrinsic or all-fiber-optic sensors. “Intrinsic” and “all-fiber” indicate that the sensing takes place within the fiber itself. In this case, the two designations can be and are commonly used interchangeably. A large and important subclass of intrinsic or all-fiber sensors is the interferometric sensors of shown in Fig. 1.3. Many of the highest-performance sensors fall into this group. The fiber sensors of Figs. 1.1–1.3 have been grouped into categories that are representative of their most common current state of development. Crossovers may occur; perhaps the most important example is the case of the interferometric sensors, many of which have been or are still being built in extrinsic or hybrid form.

From Figs. 1.1–1.3, it is apparent that virtually any environmental effect that can be conceived of can be converted to an optical signal to be interpreted. The usual case is that each environmental effect may be measured by dozens of fiber optic sensor approaches. The key is often to design the sensor so that only the desired environmental effect is measured.

Initial penetration of fiber optic sensors into markets has been driven by performance advantages. Some of these advantages are compared to conventional electronic sensors in Table 1.1. Fiber optic sensors offer an all-passive dielectric approach that is often crucial to successful applications, including electrical isolation of patients in medicine, elimination of conductive paths in high-voltage environments, and compatibility with placement in materials. The light weight and small size of these devices are critical to such areas as aerospace and provide substantial advantages to many products. Coupled to the issue of size and weight is immunity to electromagnetic interference. Conventional electrical sensors often require heavy shielding, significantly increasing cost, size, and weight. Environmental ruggedness provides key opportunities for fiber optic sensors, including high-temperature operation and all-solid-state configurations capable of withstanding extreme vibration and shock levels. Complementing these attributes are high sensitivity and bandwidth of fiber optic sensors. When multiplexed in arrays of sensors, the large bandwidth of the optical fibers offers distinct advantages in their ability to transport the resultant data.

Early work on fiber optic sensors generally fell into two distinct categories. Relatively simple fiber optic sensors were developed rapidly into commercial products, often by small firms, to perform measurements in specialized markets. An early example was the measurement of temperature in high-voltage environments. More complex fiber sensors such as fiber optic gyroscopes and acoustic hydrophones arrays were pursued by large industrial firms, complemented by government programs in an effort to access potentially large, high-payoff markets. Initial penetration into markets directly competing with conventional sensor technology from 1980 to 2000 was slow, due largely to the high cost of a limited

TABLE 1.1 Advantages of Fiber Optic Sensors

Passive (all-dielectric)
Light weight
Small size
Immunity to electromagnetic interference
High-temperature performance
Large bandwidth
Environmental ruggedness to vibration and shock
High sensitivity
Electrical and optical multiplexing
Component costs driven by large commercial telecommunication and optoelectronic market

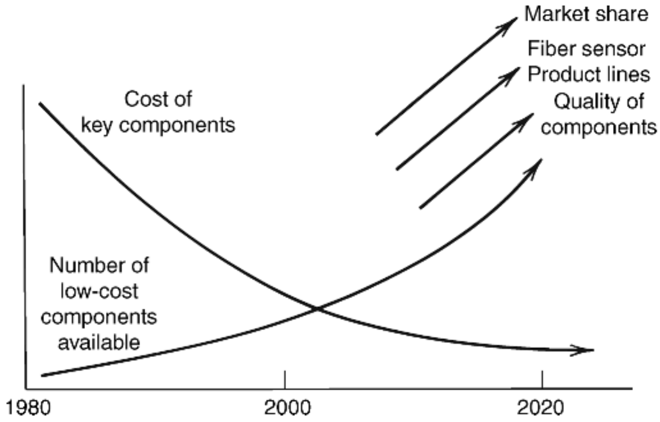

Figure 1.4 Trends for fiber optic sensors.

number of suitable components. This situation has started to change, and trends for the future are extremely positive. As illustrated in Fig. 1.4, the cost of key optical elements has been falling rapidly, while the number and variety of choices has been increasing. These factors have been complemented by increasing reliability and quality of components.

The net result has been a rapidly expanding array of fiber optic sensor products and the start of significant market penetration. Table 1.2 illustrates the dramatic trends for a few key elements. Single-mode laser diodes in the late 1970s were a few thousand dollars each and often had lifetimes on the order of a few hours. By 2000, these elements were being used by the millions for compact disc players and laser printers, with costs dropping to a few dollars per unit and lifetimes measured in tens of thousands of hours. Single-mode fiber costs in the late 1970s were on the order of $10 per meter and it was difficult to obtain. In the 1990s, it became the standard of the telecommunication industry with millions of kilometers of fiber being laid each

TABLE 1.2 Critical Components for Fiber Optic Sensors are Increasing in Performance While being Lower in Price

	1980	2000	2020
Laser diodes	$3000 each (prototypes)	$3 each (compact disc players)	<$1 each (CD and DVD players)
Single-mode fibers	$5–10 per meter (limited availability)	$0.10 per meter (standard telecom)	<$0.05 per meter (standard telecom)
Integrated optic modulators	Laboratory devices	$500 each	$50 each (fiber optic gyros)
Fiber optic gyros	Laboratory devices	$500–5000 each (low- to medium cost navigation, early use)	$500–1000 each (widespread use)

year and costs were less than $0.10 per meter. Both these developments represented improvements in cost of about three orders of magnitude, and the improvements in quality and uniformity were equally dramatic.

Following behind these basic elements were more complex devices, such as integrated optic modulators, which were laboratory curiosities in the late 1970s and far from being a product. In 2000, these elements were available in small quantities for several hundred dollars each. By the year 2020, one could fairly safely project that their cost would fall at least to about the $50 level, based on the emergence of future products, including the fiber optic gyro. This sensor, which itself was a rare laboratory device in the last 1970s, relies on integrated optic phase modulators as a key element. In 2000, these devices were being marketed widely with prices from $500 for a low-end unit supporting a delivery truck to $5000 for aircraft navigation. To further penetrate the mass market, the cost must fall to about $500 –$1000 each for modest-performance devices. This in turn will drive the necessary cost of the phase modulator down to about $50 each.

With each new successful product, the cost of existing and newly introduced components continues to drop, opening the door for new waves of fiber optic sensor products. This situation is illustrated by in Figs. 1.5 and 1.6. In 1980, there were very few components available and their cost was relatively high, leading to the application of fiber optic sensors to small-niche markets often involving only a few items. By 1990, the prices of components of fiber and light sources and fiber beam splitters fell dramatically, and multiplexing elements were readily available at moderate cost. Several new elements, including integrated optic devices, were also being introduced at relatively high prices. These developments allowed the introduction of fiber optic sensors in instrumentation to support manufacturing, the introduction of sensors for the electric power industry, and the introduction of a limited numbers of sophisticated prototype fiber optic sensors such as the fiber optic gyro. By the year 2000, the number of devices available at low cost grew substantially, allowing fiber optic designers to produce a wide variety of devices that offered superior performance at lower cost than the existing technology while enabling the use of sensors in totally new areas of endeavor. These developments would include replacement of conventional spinning mass inertial sensors with fiber optic gyros, widespread use of fiber optic sensors in process control and manufacturing, and initial demonstration of fiber optic health monitoring systems in the aerospace and construction industries. By 2010, fiber gratings were used to support health monitoring functions on bridges and dams. The fiber gyro was standard equipment on the Boeing 777 and Dornier commuter aircraft and after years still served to navigate the Spirit and Opportunity rovers on Mars. Oil and gas service companies made major investments in fiber optic sensor technology to support exploration and extraction of oil and gas and newer applications such as robotic surgery began to be seriously considered. In the future, the breadth and scope of fiber optic sensor applications can be expected to continue to increase. Areas that are expected to see rapid growth by 2020 include expanded medical instrumentation especially in the area of robotic surgery where great cost savings and improved safety may be realized; rapid growth of fiber optic health monitoring and damage assessment systems in civil structures such as bridges, buildings, and dams; and continued

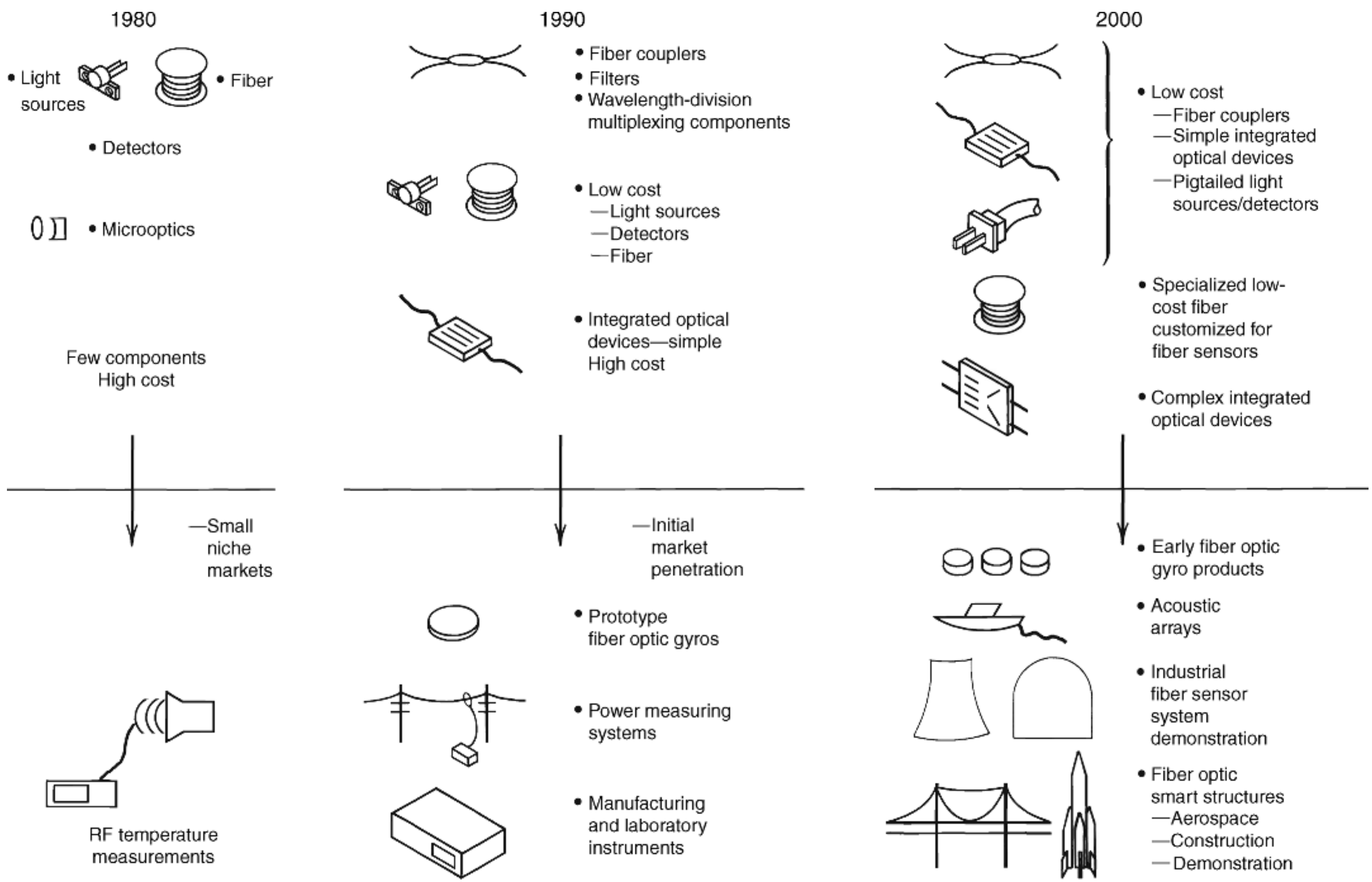

Figure 1.5 As the number of components increased and their costs dropped, the options for fiber optic sensor designers multiplied.

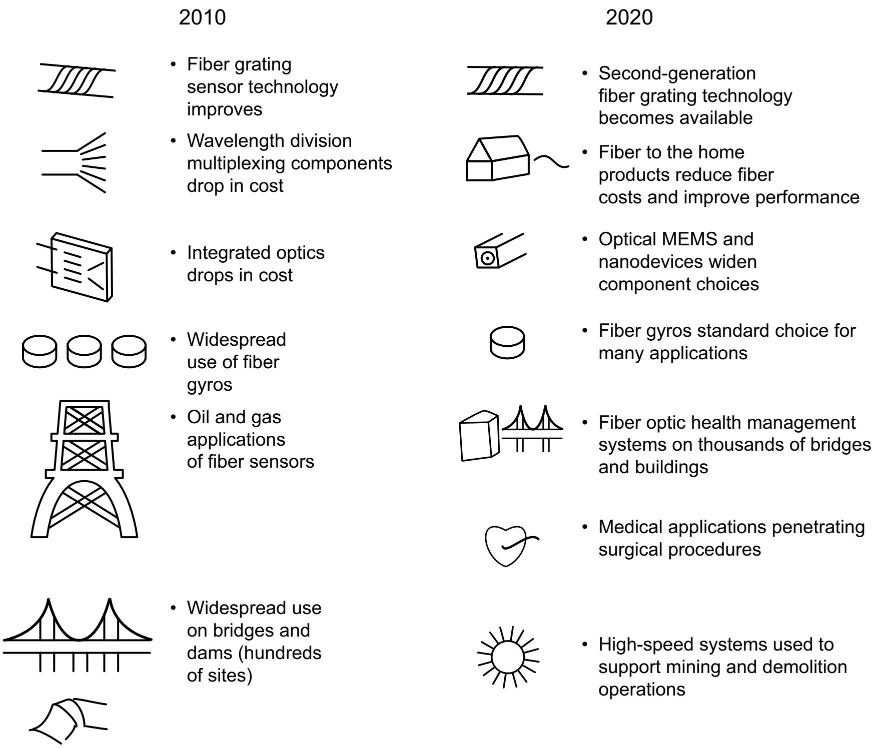

Figure 1.6 As fiber optic sensor systems continue to mature, they are finding their way into systems applications.

expansion in aerospace and industrial applications where ever-increasing capabilities and lower costs make fiber sensors more and more attractive to end users.

As these developments occur, there will be a continuing merger of telecommunications and fiber optic sensor technology into larger and more sophisticated systems. Buildings will be constructed using fiber systems to provide networking of all occupants to essential data services while serving the dual function of monitoring temperature, humidity, and power usage and relaying the essential information to the central controller. The bandwidth and sensing capabilities of optical fibers allow possibilities that are far beyond the current state of the art. Similar services will be provided to entire communities, eliminating the need for manually checking gas and electric meters, and offering centralized home security systems and fire protection and coordination of emergency services.

To make these dreams a reality, it will be necessary to develop techniques and methods of transforming basic materials into optical components, optical components into fiber sensors, and fiber sensors into useful systems. The remainder of this book is devoted to an overview of selected topics in each of these areas and describing approaches that have been useful and offer promise. It is our hope that readers of this book will find many useful tools with which to build a new and better future.