

OPTICAL SENSOR TECHNOLOGIES**Measurands and Sensor Categories**

At this point in the evolution of optical sensing technology, one can measure nearly all of the physical measurands of interest and a very large number of chemical quantities. The measurands possible are listed in Table 6.1.

Table 6.1
Optical Sensor Measurands

Temperature	Chemical Species
Pressure	Force
Flow	Radiation
Liquid Level	pH
Displacement (Position)	Humidity
Vibration	Strain
Rotation	Velocity
Magnetic Fields	Electric Fields
Acceleration	Acoustic Fields

Techniques by which the measurements are made can be broadly grouped in three categories depending on (a) how the sensing is accomplished, (b) the physical extent of the sensing, and (c) the role of the optical fiber in the sensing process.

Means of sensing

In this category, sensors are generally based either on measuring an intensity change in one or more light beams or on looking at phase changes in the light beams by causing them to interact or interfere with one another. Thus sensors in this category are termed either *intensity sensors* or *interferometric sensors*. Techniques used in the case of intensity sensors include light scattering (both Rayleigh and Raman), spectral transmission changes (i.e., simple attenuation of transmitted light due to absorption), microbending or radiative losses, reflectance changes, and changes in the modal properties of the fiber. Interferometric sensors have been demonstrated based upon the magneto-optic, the laser-Doppler, or the Sagnac effects, to name a few

Extent of sensing

This category is based on whether sensors operate only at a single point or over a distribution of points. Thus, sensors in this category are termed either *point sensors* or *distributed sensors*. In the case of a point sensor, the transducer may be at the end of a fiber the sole purpose of which is to bring a light beam to and from the transducer. Examples of this sensor type are interferometers bonded to the ends of fibers to measure temperature and pressure. In the case of a distributed sensor, as the name implies, sensing is performed all along the fiber length. Examples of this sensor type are fiber Bragg gratings distributed along a fiber length to measure strain or temperature.

Role of optical fiber

Further distinction is often made in the case of fiber sensors as to whether measurands act externally or internally to the fiber. Where the transducers are external to the fiber and the fiber merely registers and transmits the sensed quantity, the sensors are termed *extrinsic sensors*. Where the sensors are embedded in or are part of the fiber -- and for this type there is often some modification to the fiber itself -- the sensors are termed *internal* or *intrinsic sensors*. Examples of extrinsic sensors are moving gratings to sense strain, fiber-to-fiber couplers to sense displacement, and absorption cells to sense chemistry effects. Examples of intrinsic sensors are those that use microbending losses in the fiber to sense strain, modified fiber claddings to make spectroscopic measurements, and counter-propagating beams within a fiber coil to measure rotation.

Today, most of the measurands in Table 6.1 can be sensed by either intensity or interferometric techniques and as either point or distributed effects. A wide variety of physical phenomena are used to actually sense the quantity to be measured.

Advantages and Disadvantages of Optical Sensors

R&D in the optical sensor field is motivated by the expectation that optical sensors have significant advantages compared to conventional sensor types, in terms of their properties. Table 6.2 lists some of the advantages of optical over nonoptical sensors.

Table 6.2
Advantages of Optical Sensors

Greater Sensitivity	Wide Dynamic Range
Electrical Passiveness	Both Point and Distributed Configuration
Freedom from Electromagnetic Interference	Multiplexing Capabilities

Taking advantage of the capacity of optical fibers to send and receive optical signals over long distances, a current trend is to create networks of sensors, or sensor arrays. This avoids having to convert between electronics and photonics separately at each sensing site, thereby reducing costs and increasing flexibility.

A difficulty of all sensors, both optical and nonoptical, is interference from multiple effects. A sensor intended to measure strain or pressure may be very temperature-sensitive. Intense R&D over the last five years to provide means for distinguishing between various effects has been conducted for optical sensors. Considerable progress has been made, as will be discussed below.

Publication and Patent Trends

Figure 6.2 shows both the publication and the patent chronology for fiber and optical sensors combined. As indicated earlier, most sensors today involve the use of optical fibers somewhere in the technique and are referred to as optical fiber sensors. Optical sensors make use of the same physical phenomena to perform their sensing operation but involve no optical fiber. They instead rely on lens or mirror systems to transmit and

manipulate the beams of light used in their sensing process. The fiber and optical sensors field has been active slightly over a decade, with the patent record beginning earlier, as might be expected, and showing growth similar to that of publications.

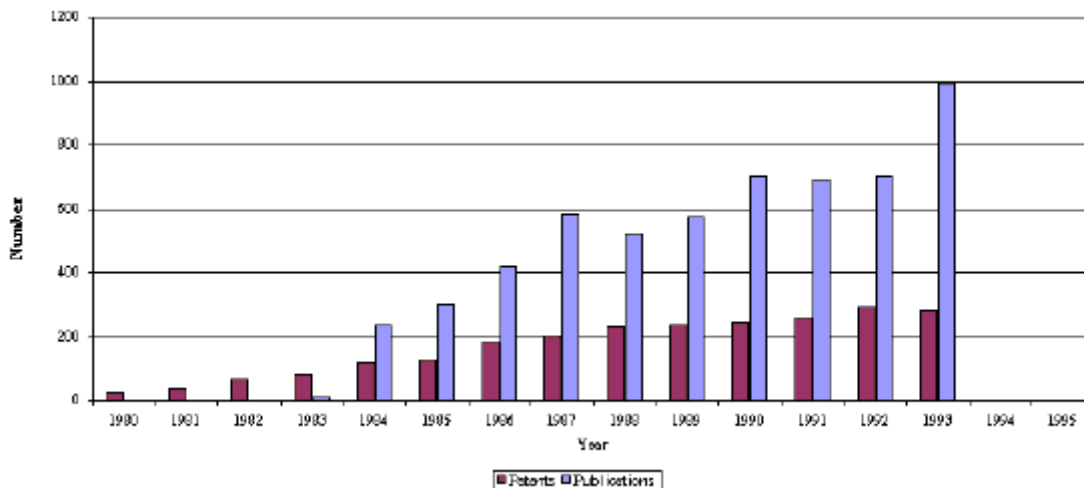


Fig. 6.2. Fiber and optical sensor publication and patent chronology (Dialog File 4; Dialog File 347 [Japan Patent Office/JAPIO Database]; and Dialog File 348 [European Patent Office Database]).

It is instructive to examine the geographic origin of both the publications and the patents. Figures 6.3 and 6.4 show, respectively, the geographical origins of publications and patents in the field of fiber and optical sensing. Clearly, the major publication work in the field has taken place in the United States and the United Kingdom. A major driving force for this has been military need for sensors that make use of the intrinsic advantages listed in Table 6.2.

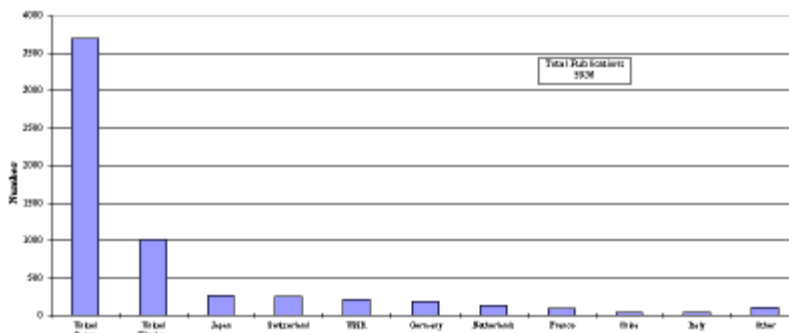


Fig. 6.3. Geographic origin of publications on fiber and optical sensor technology.

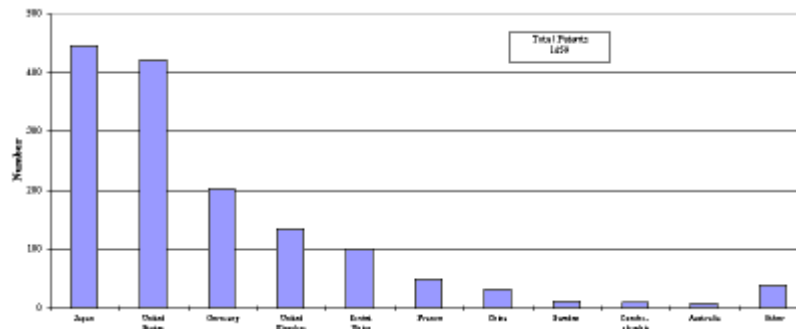


Fig. 6.4. Geographic origin of fiber and optical sensor technology patents.

The geographic origin of the majority of patents is very different from that of publications. While Japanese organizations accounted for less than 10% of technical publications, they accounted for about 31% of patents and are the largest contributors (Fig. 6.4). U.S. organizations are the second largest patent contributors, with about 29% of total patents. Differences in U.S. and Japanese patent laws probably account for the discrepancy in geographic representation in the publications and patents figures: Japan has a first-to-file patent system (distinct from the U.S. first-to-invent patent system), and the Japanese tend to use their patent system as a combination publication and patent vehicle.

It is useful to divide the approximately 6,000 papers published on optical sensors worldwide into the major enabling technology and market application categories shown in Figure 6.5. Work in each of the major categories is summarized briefly in the following sections. The major fiber and optical sensor types with direct market application are chemical, temperature, strain, biomedical, electrical and magnetic, and rotation types. These will be discussed in decreasing order of publication activity. The enabling sensor technology category covers specialty fibers, detectors, and light sources; the networks and instrumentation category covers a variety of sensor systems for monitoring multiple sensors; and the "other" category covers pressure, displacement or position, vibration, refractive index, flow, and acceleration.

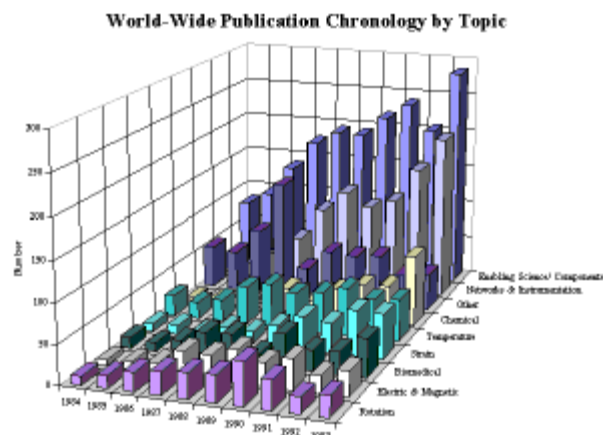


Fig. 6.5. Optical sensor publication chronology, by category.

Sensor Types

Because of the myriad ways now available to sense the same quantity, no single sensing technique has emerged to become the large-volume leader. Some techniques, however, seem to be more prominent than others for sensing a given measurand, and each technique tends to have its own specialists among the company and university labs. This is definitely a field in which new technologies are being developed and tested continuously; it is this plethora of new techniques that leads to the fragmented nature of the optical sensor marketplace.

Chemical sensors

For the most part, chemical sensors are examples of remote spectroscopy using fiber optics as a relay vehicle. Both absorption and fluorescence spectroscopy are used. Chemical testing has been demonstrated using fiber-optic fluorimmunoassay (FOFIA). In this technique, antigens specific for the antibodies to be detected are immobilized in proximity to a guided optical beam. The antibodies are tagged with fluorophores and allowed to bond to the antigens. Evanescent excitation of the fluorophores and/or collection of the resulting fluorescent radiation provide for extremely sensitive monitoring techniques. In some tests, 10^{-12} molar levels of creatine kinase (CK-MB) have been detected (Walczak et al. 1992).

Recently reported work at the University of Strathclyde (UK) includes methane sensing based on using the evanescent or retroreflected wave from a D-fiber (shown later in Fig. 6.7) (Jin et al. 1994). The readout device utilizes an AC Fabry-Pérot interferometer.

Groundwater and soil contamination monitoring has been demonstrated at the 5 ppb level by Lawrence Livermore National Laboratory (LLNL) using spectral absorption resulting from the chemical reaction between the species to be detected and a reagent (Milanovich et al. 1994). Specifically, trichloroethylene (TCE) has been detected at these levels using as the reagent pyridine, which reacts to form a colored compound that absorbs in the green portion of the optical spectrum (530-570 nm).

In a novel use of coherent fiber bundles, each fiber is used as a separate channel for a distinct species to be detected. By photoinitiated bonding, different analytes can be attached to the distal ends of fibers in the bundle, each analyte specific to a given chemical species. In a collaboration between LLNL and Tufts University, the fluorescent reflection spectrum from the analyte-specific polymer is monitored to obtain the chemical concentration of the analyte (Healey et al. 1994).

Distributed chemical sensing can be done by attaching an optical fiber to the side of a plastic rod coated with an appropriate polymer. For example, hydrogel polymer can be dip-coated onto a glass-fiber-reinforced plastic rod. Upon contact with water, resultant swelling of the polymer produces microbending losses in the optical fiber, which can be detected using an optical time domain reflectometer (OTDR) (Wallace, Yang, and Campbell 1994). Various gels can be used to detect different effects; for example, some

hydrogels do not show this swelling effect unless the pH exceeds a predetermined value; hence, pH can be measured remotely.

The principal companies building chemical sensors include Pharmacia Biotech (Sweden), which sells a nonfiber-optic device (Crossley 1994). Companies selling pH instruments include CDI/3M; Optical Systems and Sensors; Lightsense, which in addition sells a blood gas monitor; and Synectics Medical, which sells a bile sensor developed at the Italian lab CNR/IROE. Fiberchem sells a hydrocarbon monitor based on sensing changes in the cladding refractive index along a fiber. The Quantum Group, Inc., has commercialized biomimetic optical sensors for carbon monoxide (CO); it manufactured more than 3 million units in 1994 (M. Goldstein, President, private communication with the author). These are based on two-wavelength spectral changes in a secondary species.

Temperature sensors

Temperature sensors probably constitute the largest class of commercially available optical sensors. Many different physical phenomena are used to perform the sensing, each with attributes suitable for a particular application; no single technique can accommodate the entire range of temperatures and resolutions required for different applications. The main physical techniques in use are remote pyrometry (or blackbody radiation monitoring), Fabry-Pérot interferometers to measure optical path-length changes in a material, Raman scattering, and rare-earth absorption and fluorescence monitoring. The range of operation for all these techniques is very broad, with reported values from -50 deg. C to over 1000 deg. C. Sensitivity can be at the +/- 0.1 deg. C level, with newer techniques perhaps 100 times better. The U.S. and European work in this area is primarily in small companies and universities. In contrast, in Japan, large companies like Hitachi and Sumitomo are the significant players.

The U.S. military need for temperature sensors has been at the high-temperature range for fire monitoring and engine control. A number of optical fiber sensors were tested over two temperature ranges of 0 deg. C to 400 deg. C and 400 deg. C to 1100 deg. C in a program sponsored by the U.S. Office of Naval Research in 1992 (Day et al. 1994). The operability of temperature sensors was established, but no one device could accommodate the entire range.

The major activity in Japan seems to be in distributed temperature sensing. It appears to have begun with the electric power industry but now is being considered for the civil infrastructure. Applications include temperature monitoring in ducts and tunnels, nuclear plants, steel manufacturing plants, mines, and large halls. Additionally, distributed temperature sensors have been used to monitor the curing temperature of concrete to achieve the optimum structural strength in dam and building construction.

At present, activities in point-sensing of temperature appear to be stronger in the United States and Europe, while activities in distributed sensing of temperature are stronger in Japan. That trend is expected to continue. Table 6.3 is an attempt to identify the current

capabilities in these two areas of temperature sensing. The various techniques are discussed below in greater detail.

Table 6.3
Fiber-optic Temperature Sensor
Performance

Parameter	Point Sensing	Distributed Sensing
Range (°C)	-50 → 1100	-10 → 500
Accuracy (°C)	± 1	± 1
Resolution (°C)	± 0.1	± 0.1
Length Resolution (meters)	NA	1-5

Remote pyrometry This technique uses optical fibers to telemeter the black-body spectrum of a small piece of material such as sapphire to an appropriate measurement site. Typically this is used in high-temperature applications. Companies working in this area include Luxtron and Celect Electronics (Crossley 1994).

Fabry-Pérot (FP) interferometers These temperature sensors measure the change in optical path length of a short piece of material whose thermal expansion coefficient and refractive index as a function of temperature are known. In some cases, multiple wavelengths are used to null out secondary effects such as strain or pressure in the material being measured. The FP is often made in materials such as glass, calcite, or zinc selenide (ZnSe), to name a few. Because of material choices in packaging, these sensors are limited to perhaps 400 deg. C. Companies using this technique include Photonetics (formerly Metricor) and Sira, Ltd.

Fluorescence emission Temperature is most often determined by measuring the fluorescence emission decay times from rare-earth-doped and transition-metal-doped phosphors. Neodymium-doped glass shows good performance over the range -50 deg. C to 300 deg. C (Fericola and Crovini 1992). Chromium:LiSAF crystal has shown high sensitivity from 0 deg. C to 100 deg. C and is suitable for biomedical sensing (Zhang, Grattan, and Palmer 1992). Yttrium oxide and yttrium orthovanadate activated with europium (Eu) are suitable only for measurements in the 500 deg. C to 1000 deg. C range (Noel et al. 1992). Recently, Cr:YAG has been shown to operate over the range -25 deg. C to 500 deg. C. By using a digital signal processing scheme for the decay measurement, resolution of 0.1 deg. C over the entire range is possible (Fericola and Crovini 1994). Companies interested in this technique include Nortech Fibronics of Canada, whose products operate in the range -40 deg. C to 250 deg. C; Optrand, Inc., which sells devices for high-temperature engine control applications; and Takaoka Electric, which has taken over the activities of ASEA (Crossley 1994).

Distributed sensing In the distributed temperature sensing area, Hitachi makes use of the thermal properties of Raman scattering in the material of a conventional optical fiber (see Hitachi site report in Appendix D). The company has a commercial product referred to as Fiber Optic Temperature Laser Radar (FTR). In this technique researchers use a large pulsed Nd:YAG laser (~100 watts) to excite Raman scattering, which is monitored using

OTDR. Hitachi's commercial unit will operate over the range -10 deg. C to perhaps 500(C, depending on the fiber sheath material, with a quoted accuracy of +/- 1 deg. C, and a resolution of +/- 0.1 deg. C. The response time for this readout is between 15 and 90 seconds, depending on the unit. The longest length over which the OTDR technique has been successful is about 30 km. Sumitomo Electric has reported that using a distributed Er-doped fiber, temperature distribution along this length has been measured, with +/- 2.3 deg. C sensitivity and 6.5 m resolution (Wakami and Tanaka 1994).

Promising new optical sensor technologies Although still in the research or development phase, several new activities show promise for improved capability. Using a Brillouin gain spectrum analysis, temperature and strain can be measured along the length of a fiber. Nippon Telephone and Telegraph (NTT) has demonstrated a technique using OTDR readout and finds a sensitivity of 1 MHz/deg. K (Shimizu, Horiguchi, and Koyamada 1994). Temperature and length resolution are better than 0.5 deg. C and 60 meters, respectively. NTT has demonstrated this technique in two branches of a tree-and-branch network.

Building on the work in Er-doped fiber amplifiers for telecommunications, a high-temperature point sensor utilizing the green fluorescent intensity of Er-doped silica fiber has been demonstrated. This is based on the recently observed fast thermalization between the $^4S_{3/2}$ and the $^2H_{11/2}$ levels of Er. The relative population of these levels is represented well by a Boltzman distribution and thereby is related well to temperature. This technique was demonstrated between 300 deg. K and 1000 deg. K (Maurice et al. 1994). Researchers at China's Zhejiang University Department of Physics are attempting to Cr-dope sapphire crystals to fabricate a "mini-black-body radiator" with a range of over 2000 deg. C (Shen et al. 1994). They also report making Y-doped zirconia single-crystal fibers 300-500 microns in diameter and 100-250 mm in length. These should also be capable of operating at over 2000 deg. C.

A very promising area, demonstrated by several groups, builds on the temperature-sensing capabilities of fiber Bragg grating (FBG) devices. A challenge is to fabricate a device that responds to just one measurand, that is, temperature; some progress has been made. At the Universities of Kent and Southampton, two identical FBGs have been interferometrically monitored (Rao and Jackson 1994). By incorporating these in a bimetallic beam, temperature was reliably measured independent of other effects, with +/-1% linearity achieved over the range 25 deg. C to 65 deg. C, and with a possible resolution of +/-0.006 deg. C.

In related work, the reliability of the germanium-silica fibers in which the FBG are fabricated has been studied (Morey, Meltz, and Weiss 1994). The fibers seem to show creep above 650 deg. C. Calculations suggest that germania diffusion at temperatures as high as 370 deg. C is not a significant problem; however, due to this effect, the Bragg gratings could produce a shift of 1% in the measurand within 2.8 years at 650 deg. C and within 100 hours at 800 deg. C.

Strain sensors

Strain is measured by several methods, including fiber Bragg gratings, stimulated Brillouin scattering, and polarimetry in birefringent materials. Of these techniques, the FBG technology seems currently to be most preferred. In this technique a refractive index grating is written into a single-mode germanium-doped silica fiber. Strain is sensed by monitoring the reflected or transmitted wavelength from the grating as it is subjected to elongation. These gratings are easy to produce and should therefore be cost-effective. NRL and United Technology Research Center have had active programs in the area for several years. Using an interferometric readout for the reflected wavelength, NRL has recorded sensitivity of about 10^{-13} (strain (A. Kersey, private communication with the author, February 1995).

Other laboratories working in this area include the Institute for Optical Research in Sweden, which has used a two-core fiber with FBGs to simultaneously measure both temperature and strain (Wosinski et al. 1994). Strain sensors based on FBG are also sensitive to temperature. Workers at the Department of Physical Sciences at Waterford Regional Technical College in Ireland and the Department of Physics at Herriott-Watt in Scotland have used dispersive Fourier transform spectroscopy to measure a set of parameters for both temperature and strain and extract the competing effects (Flavin, McBride, and Jones 1994). They measure 18 microstrain with their technique.

As noted above, two identical FBGs can be used to nullify temperature effects. Using these two FBGs in a strain sensor, as little as 9 microstrain was measured independent of temperature (Rao and Jackson 1994).

Using Brillouin OTDR as for temperature measurement, NTT has demonstrated sensitivity values of 5 MHz/0.01% strain. In two branches of a tree-and-branch network NTT has shown a length resolution of 60 meters and a strain resolution of about 50-100 microstrain.

Biomedical sensors

Development of fiber-optic sensors for medical applications began nearly 20 years ago. The proven success of biomedical optical sensors results from their reliability and biocompatibility and the simplicity of the sensor-physician interface. Both invasive and noninvasive types have been developed and manufactured. Nearly all of the activity in this sensor area is in the United States and Europe; few Japanese contributions are present in the published literature. For the most part, sensors are currently based on silica or plastic fibers that are coupled to sensitive sections called optodes, and they utilize intensity modulation interrogation schemes. An emerging group of sensors is based on mid-IR (infrared) transmitting fibers. Many of these make use of spectroscopy in some fashion, either by using the directly transmitted or reflected light or by examining the fluorescent return from some material that acts as an extrinsic sensor. Many involve use of dual wavelengths to enhance sensitivity.

The following two activities are specific examples of spectroscopic biomedical sensors. Using the correct fluorophores on the ends of three fibers, pH, carbon dioxide, and

oxygen can be simultaneously measured. Such a unit has been developed by CDI-3M Health Care, based on a system designed by Gehrich et al. (1986). CDI-3M has also developed a disposable probe for extracorporeal blood gas analysis (Baldini and Mignani 1994); it manufactures about 10,000 a month. Two other companies, Biomedical Sensors (UK) and Puritan Bennet Corporation (U.S.), make similar sensor heads. Oximetry in the blood is typically measured by exploiting the different absorption spectra of the hemoglobin and oxyhemoglobin in the near-IR (Baldini and Mignani 1994). Several invasive oximeters are commercially available from Oximetric in Mountain View, CA, and BTI in Boulder, CO.

Flow monitoring by laser Dopplerimetry is used in several biomedical sensing applications, including dermatology for testing of skin irritants, gastroenterology via endoscopes for making blood perfusion measurements in the stomach and duodenum, etc., and dentistry for contact probes to measure blood flow in the teeth and gums. Sensors are used in internal medicine for angiology and vascular surgery to monitor blood flow during vascular reconstruction and the degree of arteriosclerosis in arteries, and they are used in orthopedics for monitoring the blood perfusion in tissues during and after surgery. The most common types of probes rely on spectral monitoring of the backscattered light. Companies making probes of this type are Perimed in Sweden and Applied Laser Technology in the Netherlands (Baldini and Mignani 1994).

Gastroenterology *in vivo* monitoring is also being performed using spectroscopic techniques together with optical fiber light transport. In one technique, light from blue and green LEDs (light-emitting diodes) is transmitted through fibers to a small cavity between the fiber end and a retroreflector; any gastric fluids present are monitored by examining the relative spectral response. Prodotec (Italy) and Synectics (Sweden) have commercialized such a device (Baldini and Mignani 1994).

Fibers are used in a major ophthalmologic application: the detection of cataracts. By simply monitoring the backscattered light intensity from the lens of the eye, the onset of alpha-crystallite aggregation can be detected by autocorrelation measurements. The onset is delineated by a bimodal distribution of particle size in the backscattered radiation.

Short lengths of heavy-metal-doped fibers are used in monitoring radiation treatment for oncology patients. A simple differential attenuation measurement reliably reads dose level. Hyperthermia treatment of tumors relies on temperature monitoring during microwave or radio frequency irradiation. Luxtron (CA) developed one of the first such sensors based on the fluorescence spectrum of rare earth dopants in the fiber. Several other sensors based on Fabry-Pérot interferometer cavities and mid-IR pyrometry are being developed.

In the area of neurology, head trauma patients often require continuous monitoring of intracranial pressure; this is being done by fiber-optic catheters tipped with a small displacement diaphragm in front of two fibers. Simple monitoring of the retroreflected energy back into the second fiber measures diaphragm displacement and hence pressure. FP interferometers have also been used, as described below in the section on pressure

sensors. A low-cost disposable probe is made by Camino Labs (CA) (Baldini and Mignani 1994).

Electrical and magnetic sensors

Optical fiber sensors are an appealing choice for measurement of electric and magnetic fields and electrical current, because of their inherently dielectric nature. They provide galvanic isolation of the sensor head from ground potential, are less sensitive to electromagnetic interference, generally are of small size, and provide superior safety. Nearly all electric and magnetic field sensors based upon fiber optics are hybrid devices; that is, the fiber is attached to some other material and is used to monitor any changes in that material with electric and magnetic fields. This is required for electric fields since the intrinsic inversion symmetry of the glass matrix of the optical fiber precludes a Pockels effect; it is required for magnetic fields because the Verdet constant of telecommunication optical fibers is very small. Therefore, the fiber typically is used to sense dimensional changes of a piezoelectric or piezomagnetic material in the presence of electric and magnetic fields. Depending on the level of sensitivity required, the readout can be either by simple intensity measurement or by interferometric techniques. Because the fiber is sensitive to temperature, much of the present work is focused on removing that sensitivity.

In Sweden, the ABB Corporate Research Center has had ongoing field tests of interferometric current and voltage sensors that have been integrated into the gas-insulated high-voltage switch gear of a 220 kV station. For voltage sensing, the fiber is wound around quartz crystals and the resulting piezoelectric induced stress in the fiber is monitored with a white-light interferometer. Voltages from 0.1 to 1600 V are measured with errors well below 1% (Bohnert, Brandle, and Frosio 1994). The current sensor is based on using a modified fiber gyroscope readout to monitor the Faraday effect in an ultra-low birefringence fiber 100 meters in length. ABB reports a maximum detectable current of >23 kA, a sensitivity of about 2 A, and a relative error of +/-0.15%.

Making use of the higher Verdet constants of SF57 glass, Siemens has demonstrated a current sensor based on measuring the rotation of the plane of polarization from traversing a reflecting ring of this material (Bosselmann and Menke 1994). Using a ring made of yttrium-iron-garnet (YIG), NIST scientists have built similar devices. The YIG has a Verdet constant of about 0.007 rad/A, compared to that of SF57 glass, which is about 0.00002 rad/turn. NIST has reported minimum detectable current of about 220 nA/ \sqrt{Hz} (Rochford et al. 1994).

The same iron-garnet materials are used to sense magnetic fields. Using a 25 mm length of gallium-doped YIG together with flux concentrators, magnetic field sensitivity of about 1.4 pT/ \sqrt{Hz} has been reported in a very simple polarization rotation experiment (Deeter et al. 1993). This is believed to be the most sensitive value observed.

The most sensitive voltage sensor reported is based upon an electrostrictive transducer made from lead-titanate-doped magnesium niobate with about 65 meters of fiber wrapped

around it. The readout is accomplished interferometrically with the use of a dither frequency to remove noise. The interferometer is held at quadrature, and a phase-sensitive detection is used. Voltage sensitivity as low as $20 \text{ nV}/\sqrt{\text{Hz}}$ has been reported (Fabiny, Vohra, and Bucholtz 1994).

The Naval Research Laboratory has reported measurement of high magnetic fields by using an FBG. It was observed that the reflectance of the FBG as a function of wavelength was different for right and left circular polarizations. By interferometrically reading the phase difference due to FBG wavelength shifts, minimum detectable magnetic fields of about 2 gauss were possible. The dynamic range is very large, and fields of 100 Tesla (10^6 gauss) are measurable (Kersey and Marrone 1994).

Hoya Glass and Tokyo Electric Power Co., Inc., have collaborated on a fiber-optic current sensor. The single-mode fiber is made of a flint glass (high in lead) and therefore has a large (relative to telecommunication grade fiber) Verdet constant, but it also has relatively high transmission loss. Nevertheless, Hoya and Tokyo Electric Power are able to fabricate a 3-turn, 10 cm coil and obtain polarized transmission with good (~ 35 dB) extinction (Kurosawa et al. 1994). A superluminescent diode is used as the light source. Current is measured by observing the polarization rotation through crossed polarizers.

Matsushita Electric Industrial Company is building similar current sensors based upon thin garnet magneto-optic films inserted in a gapped toroid (Itoh et al. 1995). Unpolarized light from an 880 nm LED is transmitted to the sensor via a multimode fiber. In a new design, ball lenses are used to quasi-collimate the beam from the 80 microns diameter fiber and direct it through two polarizers and the thin garnet film. The film is a 50-m-thick BiGdLaYFe garnet. A 200-micron-diameter fiber is used to collect the output beam. System loss is about 13 dB, and 1% linearity is achieved.

Matsushita is now selling an earlier version of this current sensor ($\sim 5\%$ linearity) to one of the Japanese utility companies, Kansai Electric Power Company, for use as a current fault sensor (G. Day, private communication with the author, March 1995). The unit is located at "switching" stations between the substations and consumers, and it services about 100 customers. The expected lifetime of the device is 20 years. Even at present volumes, the price of the sensor head (transducer, optics, and fiber-optic links) is surprisingly low. The costliest component, which is roughly 25% of the cost of the device, is the polarizer (Corning Polarcor). In 1995, Matsushita began the third year of a seven-year agreement with Kansai, delivering about 1,000 units a year. Eventually, Matsushita envisions selling the 1%-linearity version in much higher volumes. Company managers see considerable competition in Japan from Sumitomo Electric, Toshiba, Mitsubishi, NGK Insulator, Furukawa Electric, Tokyo Electric Power, Fujikura, Hitachi, and Fuji Electric. At the present time, the ranges for electric and magnetic field sensors and current sensors are 0 to ± 100 kV, 0 to 100 Tesla, and 0 to ± 25 kA, respectively. The highest sensitivities reported (see above) are $20 \text{ nV}/\sqrt{\text{Hz}}$, $1 \text{ pT}/\sqrt{\text{Hz}}$, and $200 \text{ nA}/\sqrt{\text{Hz}}$, respectively. More likely sensitivity values in commercial sensor units are thought to be 200 to 2000 $\text{nV}/\sqrt{\text{Hz}}$, and 10 to 100 $\text{pT}/\sqrt{\text{Hz}}$ for electric and magnetic field sensors. For sensing very high electric and magnetic fields, Ezekiel et al. (1994) have demonstrated a

two-photon technique for measuring Stark or Zeeman splittings of spectral lines using evanescent wave propagation in a fiber to probe a surrounding gas whose levels are split. If even higher fields are present, the hyperfine structure can be examined. This technique is being referred to as stimulated Raman gain spectroscopy (SRG).

Rotation sensors

Two types of optical rotation sensors have been developed over the past decade, both based on the Sagnac effect: the ring laser gyroscope and the fiber-optic gyroscope. When two light beams propagate in opposite directions around a common path, they experience a relative phase shift depending upon the rotation rate of the plane of the path. The actual heading or direction is obtained by integrating the output. In the case of the ring laser gyroscope (RLG), this phase change produces a change in the oscillation frequency of a laser that is integral to the path. In the case of the fiber-optic gyroscope, the phase difference is detected by interfering the two beams outside the path. According to Ryan, Hankin, and Kent (1992), the RLG, which is the first practical device to utilize the Sagnac effect, has now become a component of commercial inertial navigation systems (Honeywell has a contract for the Dornier 328). The FOG, however, being a simpler device, is currently receiving more attention due to its potential to achieve the required performance at a lower cost than with RLG or mechanical gyroscope technology.

The FOG consists of a loop of single-mode optical fiber (often polarization-maintaining fiber) and related coupler components, a semiconductor laser or superluminescent LED, and signal-processing electronics. The coupler components are generally fabricated in proton-exchanged LiNbO₃ integrated-optic circuits. This material is chosen for its ability to modulate the light beam for improved detection.

The important metrics of FOG performance are minimum (sensitivity) and maximum rotation rates (deg./sec.); bias drift, which is the variation in rotation rate with time due to ancillary effects such as temperature and aging; random walk, which is essentially a short-term noise in the system; and scale factor, which is the degree to which the measured rotation rate is independent of the absolute value of rotation rate. Other performance parameters include hysteresis, turn-on time, dynamic range, and spectral noise. Generally, three grades of product are identified, depending upon the values of these performance parameters: moderate, intermediate, and inertial grades. The moderate and intermediate categories of gyroscopes are being developed for industrial applications such as positioning systems, self-guided robots, and bore-hole survey systems. The inertial category is for navigation systems. Table 6.4 shows values of the important parameters for each grade.

Table 6.4
Fiber-Optic Gyroscope Requirements,
by Grade

Parameter	Moderate Grade	Intermediate Grade	Inertial Grade
Max. Rate (deg/sec)	100	100	200
Bias Stability (deg/hr)	10-100	0.1-1	0.01-0.0001
Random Walk (deg/vhr)	1-10	0.01-0.1	0.0001-0.001
Scale Factor (ppm)	10000	100-1000	1-10

Many companies are active in FOG technology, at all stages of the innovation process, and for each performance grade. Typically it seems that U.S. companies are pursuing high-performance FOGs, while Japanese companies are aiming at the moderate and intermediate device performance. The high-performance work is driven by military applications and funding, while the moderate and intermediate work addresses commercial applications. Currently, U.S. companies such as Honeywell, Litton, Northrup, Allied Signal, Smith Industries, and Draper Laboratories can achieve FOG performance at the intermediate and navigational grade levels. Most of their programs are in the development stage. In Japan, Mitsubishi Precision and JAE have indicated they also have a research capability for achieving navigational grade performance. Photonics S.A. in France also has commercially available FOGs with bias stability of a few tenths of a degree/hour and a dynamic range of ± 2000 deg/s (LeFevre 1994).

For the lower performance grades, Hitachi Cable has a number of position and orientation products for use in autonomous vehicles, such as cleaning robots and unmanned dump trucks and carriers; radio-controlled helicopters for agricultural spraying; and devices for route surveying and mapping for pipes and tunnels and for underground construction. Fiber-optic devices are attractive in the latter uses because of their immunity to magnetic fields. Hitachi claims to be the largest producer of FOGs for both industrial and commercial applications. The JTEC panel's hosts there indicated that the company is currently able to produce about 5,000 units/month (see also Hitachi Cable site report, Appendix D). In 1993, Hitachi won an R&D 100 Award for its FOG automotive navigation system, commercially deployed in certain Toyota models and used in conjunction with GPS (global positioning satellite) systems. Figure 6.6 shows the dashboard of a car equipped with one of the FOG units, as well as several other FOG applications.

New directions in the area of FOG rotation sensors include (1) obtaining better long-term stability to achieve the inertial grade performance requirements, and (2) reducing the overall cost of packaged devices. Some recent R&D aimed at higher performance makes use of telecommunications work with erbium-doped optical fiber amplifiers. This has been directed both toward making Er-doped fiber lasers and superfluorescent fiber sources (SFS) for FOG sources and toward employing the Er-doped fiber laser in a ring-laser configuration. An Er-doped ring fiber laser has been operated bidirectionally in multiple longitudinal modes with stable CW output. The ring laser produces a beat frequency proportional to the rotation rate. This work was conducted by the Department of Physics, KAIST, and the Korean Electronics and Telecommunication Research

Institute (Kim, Kim, and Kim 1994). A fiber Brillouin ring laser using polarization-maintaining (PM) fiber has been demonstrated by Tanaka at the University of Tokyo (Tanaka and Hotate 1994). The rotation is measured by the beat frequency between the counter-propagating stimulated Brillouin scattering (SBS) beams. The PM fiber removes a source of noise due to mode-hopping between the two counter-propagating beams. Finally, Photonetics researchers indicate that using an Er-doped fiber source they expect to attain 0.01 deg/hour bias stability with 1 km coils in their FOG (LeFevre et al. 1994).



Fig. 6.6. Hitachi FOG for Toyota dashboard display (upper left), cleaning robot (lower left), and autonomous dump truck and helicopter applications (right). Describing the automotive application, an Hitachi brochure states, "The FOG detects rotation of cars...allowing you to know the direction in which you are headed....and travel to the desired destination in a minimum amount of time." The Hitachi brochure also describes the important role such systems would play in intelligent vehicle highway systems.

Pressure sensors

Pressure sensors based on movable diaphragms, on small Fabry-Pérot interferometers, or on microbending, are the primary types being used today. They are finding use in biomedical, process control, marine, and engine control applications.

The first pressure sensors for biomedical usage relied on piezoresistive techniques. These were developed in the late 1950s for intravascular pressure measurements. Later, fiber sensors based on moving diaphragms and monitoring retroreflected intensity emerged (Pahler and Roberts 1977). Camino Labs in San Diego, CA, manufactures devices of this type and is reported to be producing around 60,000 devices/year.

The first FP devices were demonstrated in the late 1970s (Cox and Jones 1983), where one of two parallel reflecting surfaces moved in response to the pressure changes. Later, Metricor (now Photonetics, Inc.) developed a very compact version of this device based on anodically bonding a silicon membrane to the end of a fiber (Saaski, Hartl, and Mitchell 1986). Thus, the diameter of the sensor unit was the same as the fiber itself. Additionally, the interferometer is monitored at two wavelengths to avoid competing effects. This approach can measure pressure to an accuracy of a few percent, which is sufficient for many applications. This technique can also be adapted to measure temperature and refractive index. Sira, Ltd., produces a device based on this technology.

In the early 1980s, pressure sensors based on microbending were demonstrated (Fields et al. 1980). In this technique the fiber is positioned between two opposing serrated plates

that bend the fiber, causing signal loss in response to movement of the plates. This method can be configured to sense displacement as well as pressure. Babcock and Wilcox is one of the companies producing pressure sensors based on this technique (Berthold 1994).

For extremely high pressures, stress-birefringent polarization-based sensors have been demonstrated. A number of universities have constructed devices capable of operating over pressure ranges 0 - 100 MPa (760,000 torr) (Wolinski 1994). The current state of the art in pressure sensing is capacity to sense pressures in the range of 0 to 700,000 torr. Probably the largest of the applications, biomedical sensors, operates only in the range of 0 to 300 torr. The sensitivity of typical devices is 0.5 to 5 torr (0.01 to 0.1 psi); the best devices can sense 0.06 torr (Rao and Jackson 1994). Relatively little is reported from Japanese companies in the pressure sensor area.

Displacement and position sensors

Displacement sensors were some of the first optoelectronic sensors to be developed, beginning in the late 1970s and early 1980s. The simplest sensors rely on the change in retroreflectance of light into a fiber because of movement of a proximal mirror surface. One of the first Photonetics sensors was of this type, in which a conical tip is applied to the end of a fiber (Cartellier 1990). Light is totally reflected back into the fiber if the surrounding medium is air; however, if the fiber is inserted into a liquid matching the fiber index, light is extracted from the fiber and lost. Thus, displacement of the liquid surface can be tracked. For obvious reasons, these displacement sensors are referred to as liquid level sensors.

Babcock and Wilcox has also used microbending concepts to sense displacement by causing loss in a fiber due to serrated plates variably pressing on the fiber. Some of these sensors are reported to detect displacements as small as 10^{-10} m/ $\sqrt{\text{Hz}}$ (Lagakos et al. 1987). A more practical sensitivity might be 10 (m. As for the range of displacements possible, some of the fly-by-light sensors have been reported to operate from 0 to 50 cm.

Acoustic and vibration sensors

For the most part, fiber-optic vibration sensing has been done in the form of hydrophones for naval applications. Initial work dates to the early 1980s, when omnidirectional devices were made. Fiber-optic devices have provided equal or superior performance to conventional hydrophones in the areas of towed arrays, planar arrays, and fixed undersea surveillance arrays.

More recently, acoustic microphones have been fabricated using similar designs. The basic configuration is a coil of fiber wrapped on a compliant cylinder. As the cylinder flexes in response to the acoustic wave, the resulting stress in the fiber coil is monitored interferometrically. Much of the data is summarized in a review paper from NRL (Wang et al. 1994). The frequency response of these devices can be made very flat, from 0.01 to over 4000 Hz. They can also be made nearly independent of absolute pressure from 0.7 to

3 MPa. The most responsive of these devices can be ~ -300 dB re 1 mPa, well below sea-state zero. NRL reported on a 48-sensor towed array in 1990 and on a 49-channel planar array in 1993. Ultrasonic devices have also been reported that are capable of operating from 10 to 60 kHz.

Acoustic microphones have been fabricated by wrapping fiber around styrofoam cylinders and inserting this optical device in one arm of a Mach-Zehnder interferometer. Performance as good as commercial microphones has been reported. Above 200 Hz the noise floor can be below 20 dB re 20 mPa (Cho and Bualat 1994), and the frequency response is flat to within 2 dB up to 2000 Hz. Though unconfirmed, some U.S. researchers interviewed by the JTEC panel believe that audio microphones of this type are being made by some Japanese audio equipment manufacturers.

Miscellaneous sensors

Several other sensor types have been fabricated in fiber-optic versions: index-of-refraction sensing has been accomplished at the 10^{-5} level by monitoring the evanescent coupling between a fiber and planar waveguide (Johnstone, Fawcett, and Yim 1994). Ranges of index from about 1.3 to 1.7 can be measured. Index-of-refraction sensors are useful in food processing applications, for example, to monitor sugar content, oil of hydrogenation, or brine content of an operation. Flow sensors have been fabricated in which optical pressure sensors are used to monitor vortex shedding around a suitable obstruction or by the use of aperture plates. Accelerometers based upon sensing an angular displacement using fiber optics are reported to have a detection threshold for angular movement of 4×10^{-10} rad/ \sqrt{Hz} and acceleration of approximately 10^{-6} g/ \sqrt{Hz} (Listvin et al. 1994). Still other sensors have been reported that are not relevant to the scope of this JTEC technology assessment.

Enabling Sensor Components

Specialty fibers for sensors

Since a large percentage of today's optical sensors involve optical fibers in some form, it is important to discuss the status of fiber R&D. For much of the work, sensor designers have made use of the all-glass fibers that are readily available commercially due to high-volume use in telecommunications. Interferometric sensors need single-mode, all-glass fibers; intensity type sensors typically utilize multimode fiber for greater light-gathering capability. While high-NA (numerical aperture) plastic fibers are used for some intensity type sensors, the transmission and fluorescence properties of the plastic complicate the spectral response, so all-glass fibers are favored for many spectroscopic-type sensors. Polarized light transmission is important for a number of sensors (e.g., the fiber-optic gyroscope, FOG); many fiber devices are designed to retain this property along the length of the fiber and in the presence of macro- and micro-bending. In the case of the FOG, the requirements are for a small coil of fiber for which the bending loss must be small, the polarization properties of the light must be maintained, and the physical strength of the fiber must not be jeopardized. For many of the chemical sensors, it is important for the

light wave to interact with its surroundings. Therefore, fibers have been made where the core is close to the cladding-outside interface. An example of this type of fiber is the "D-fiber." Shown in Figure 6.7 are the cross-section views of several types of fiber manufactured and used today.

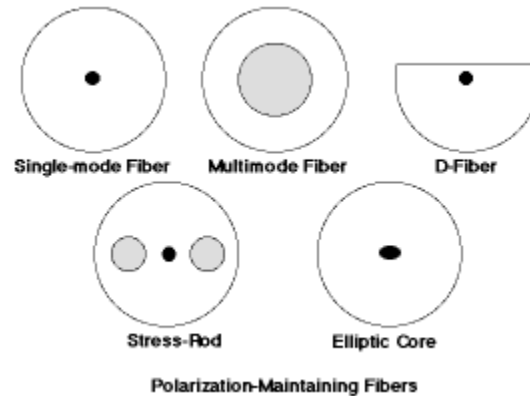


Fig. 6.7. End view of specialty fibers.

Several companies around the world manufacture optical fibers. The large telecommunications fiber manufacturers are Corning and AT&T in the United States; Sumitomo, Fujikura, Furukawa, and Optical Fibres Australia in Asia and the Pacific; and Alcatel, Pirelli, Optical Fibers Ltd., and Siecor, GmbH, in Europe. Many of these companies also fabricate special fibers required for optical fiber sensing. In addition, there are numerous smaller-volume fiber manufacturers such as 3M, Lightspec, Spectran, and Andrew in the United States; Hitachi in Japan; and York in Europe, to name a few. While it is difficult to ascertain leadership in manufacturing optical sensor fibers, due to the fact that many sensors utilize existing telecommunications fibers, it would generally seem that the United States, by virtue of its large fiber manufacturing base and fiber sensor research, has the strongest position in both the design and manufacture of sensor fibers.

Detectors

While not much change has taken place in the semiconductor devices actually used to convert photons into electrons, progress continues to be made in readout techniques for the sensor signals. Of particular note is the use of optical fiber interferometers to monitor other interferometric sensors. NRL has led this activity (Kersey, Borkoff, and Morey 1992) and has reported using fiber Mach-Zehnder (MZ) devices to monitor fiber Bragg grating laser cavities and observe strain resolutions of $1.8 \times 10^{-13}/\sqrt{\text{Hz}}$. NRL has also reported that detection of wavelength shifts in Brillouin and Bragg grating sensors has been improved recently using an all-fiber Fourier transform spectrometer. A demonstrated spectral resolution capability of 0.07 cm^{-1} corresponds to a Bragg wavelength shift of $\sim 0.015 \text{ nm}$ in the 1.55 microns region (Davis and Kersey 1994). In other detection work, workers at Photonetics report using an erbium-doped fiber source in an optical coherence domain reflectometer (OCDR) (LeFevre 1994); they observe a sensitivity of -100 dB in backreflection. Workers at the University of Tokyo are also

investigating this technique, but with the addition of phase-modulation (Hotata and Saida 1994).

Light sources

The majority of optical sensors still utilize semiconductor lasers and LEDs as light sources. Increasingly, however, the low-cost semiconductor lasers have been used to pump rare-earth-doped fibers to provide excellent, stable fluorescent sources for chemical monitoring.

A thulium-doped zirconium fluoride fiber exhibiting strong bands at 1.47 microns and 1.9 microns when pumped at 0.79 microns has been used to measure water content. It could have application in measurement of relative humidity, moisture content in paper, and monitoring of ammonia gas (MacCraith and McAleavey 1994).

Erbium-doped superfluorescent fiber sources have been developed for gyroscopes. Pumping at 980 nm, these have emerged as the preferred light sources for rotation (FOG) sensors. They avoid the unacceptably high thermal stability coefficient (~400 ppm/deg. C) for navigational gyroscopes and offer 1 ppm stability (Hall, Burns, and Moeller 1994).

Networks and Instrumentation

All early sensor demonstrations were of single-sensor units. Eventually in an effort to reduce system cost and increase reliability, several sensors were connected together in either an array or a distributed network. Sensing was accomplished using optical techniques, and only at the end of the network was the optical signal converted into an electrical signal. Various frequency and time division multiplexing techniques were used to extract the desired optical signal. The earliest array demonstrations began in about 1982 using frequency-division multiplexing (FDM) technology (Dandridge 1994). In 1988, Plessey demonstrated a 6-element time-division multiplexed (TDM) acoustic array. At NRL in the same timeframe, 10 sensors were being multiplexed using both FDM and TDM techniques. More recently, a 16-element FDM acoustic sensor (hydrophone) has been described (Yurek et al. 1993). Much of the interest in sensor arrays arises from considerations of cost and avoiding having to link multiple pieces of remote electronics with nonoptical systems. Interest is now focused upon reducing costs of the optical elements, such as 2 x 2 couplers, MZ interferometers, and FBGs. Use of multiplexed networks has also moved away from multiple semiconductor lasers to use of single, high-performance Nd:YAG lasers; the resulting cost per photon is less by 2 to 10 times.

Several recent examples of sensor networks have been reported. The European BRITE-EURAM STABILOS project is intending to use FBG technology to perform strain monitoring in mine networks for such activities as on-line excavation and blasting (Ferdinand et al. 1994). The desire is to have a temperature-insensitive concatenation of strain and pressure sensors capable of detecting <0.1% strain and 0.1 bar pressure. The strain and pressure range needed is 0 to 500 mm and 0 to 1000 bar. As many as 10

sensors per line are desired in a STAR topology. Fiber network lengths could be a few kilometers.

Arrays of fiber Bragg grating sensors have been deployed for sensing strain in bridges and other structures. Recently, 15 FBG sensors were embedded within the precast concrete girders of a bridge during their construction (Maaskant et al. 1994). It was demonstrated that these sensors can measure the change in internal strain within the girders associated with both static and dynamic loading of the bridge with a truck. The sensor arrays were used to directly test both steel and carbon composite tendons within the concrete deck support girders. This is the first bridge in the world to use carbon fiber composite tendons.