Advanced fiber grating strain sensor systems for bridges, structures, and highways

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ABSTRACT

Fiber Bragg grating sensor systems have wide application in the area of civil structures. The advantages of fiber grating strain sensors over electrical strain gauges such as greatly reduced size, EMI resistance, and higher temperature capability make them ideal choices for smart structure applications. Some of these fiber grating sensor systems can measure or detect multiaxis strain, transverse strain, temperature, bridge scouring, ice, and traffic flow.

Keywords: fiber gratings, multiaxis strain, civil structures, ice, scouring, temperature, traffic

1. MULTIAXIS STRAIN AND TEMPERATURE

Blue Road Research is developing a multiaxis strain and temperature sensor based on dual overlaid gratings written onto polarization preserving fiber[1,2] (Figure 1.) This sensor has the potential to measure simultaneously, three axes of strain and temperature (Figure 2.) When two broadband lightsources centered, for example, at 1300 and 1550 nm, are directed into a multiaxis sensor with dual overwritten gratings at 1300 and 1550 nm, four spectral peaks are reflected. Two of these peaks are associated with the two polarization axes at 1300 nm, and two are associated with the two polarization axes at 1550 nm. These four peaks give the potential for four separate pieces of information for four events, namely axial strain, two mutually orthogonal axes of strain, and temperature.

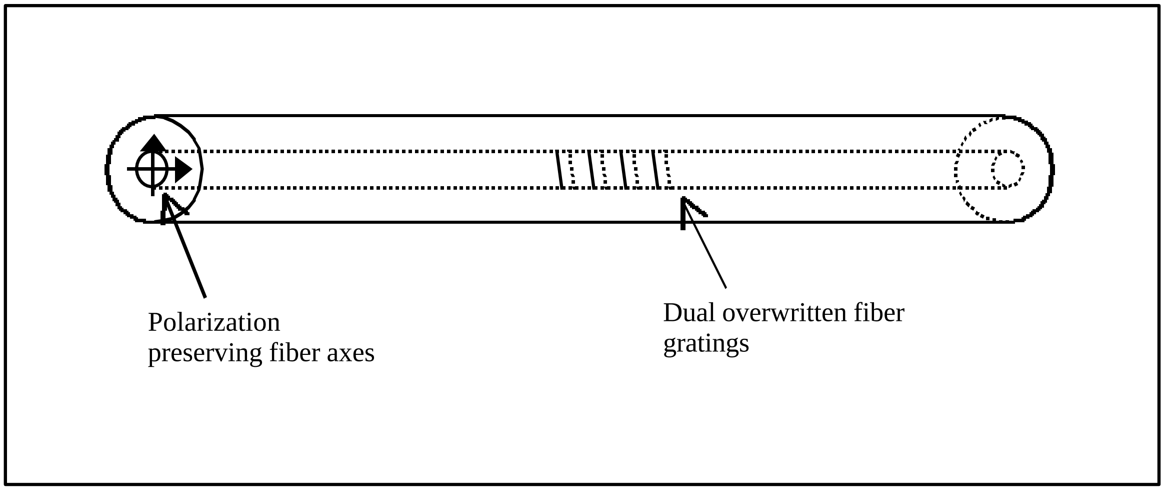

Figure 1. Multiaxis strain sensor formed by writing dual overlaid gratings onto the core of polarization preserving fiber. This configuration results in the reflection of four spectral peaks, two per polarization axis.

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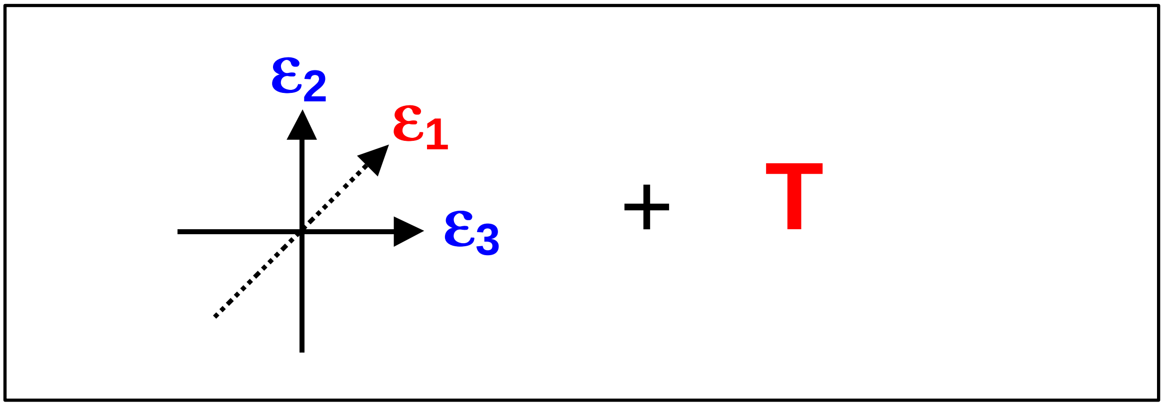

Figure 2. The multiaxis sensor has the potential to measure simultaneously 3 axes of strain plus temperature.

Axial strain has the effect of shifting the pairs of spectral peaks (Figure 3.) Axial strain (ε_1) in this context refers to strain acting along the length of the fiber sensor. Quantitative values for axial strain are realized with this spectral information. For example, a grating written at 1300 nm subjected to 1000 με (microstrain, 10^{-6} strain) will result in a spectral peak shift of 1nm.

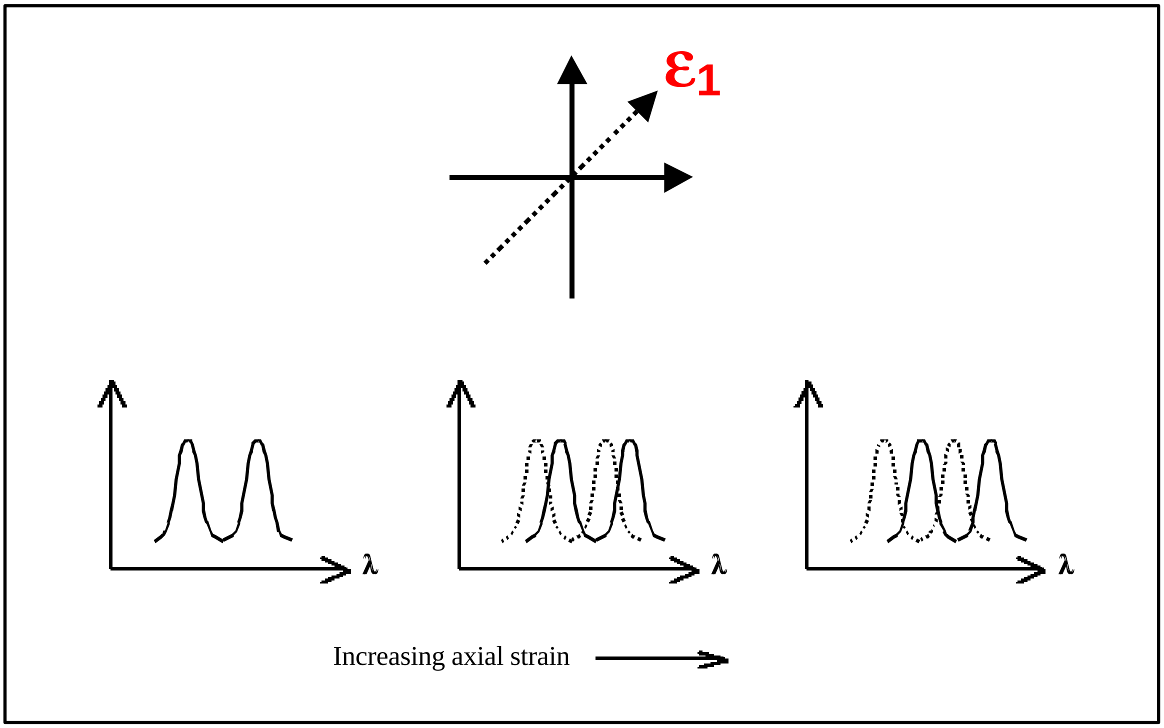

Figure 3. Spectral response of a multiaxis sensor under axial strain. Peak shifts occur for the two pairs of peaks corresponding to the two polarization axes.

Transverse strain has the effect of changing the peak separation of the pairs of peaks (Figure 4.) Two mutually orthogonal axes of transverse strain (ε_2 and ε_3) can be realized because there are two separate peak separations from the dual overlaid gratings of the fiber sensor. These peak separations also result in quantifiable values for transverse strain.

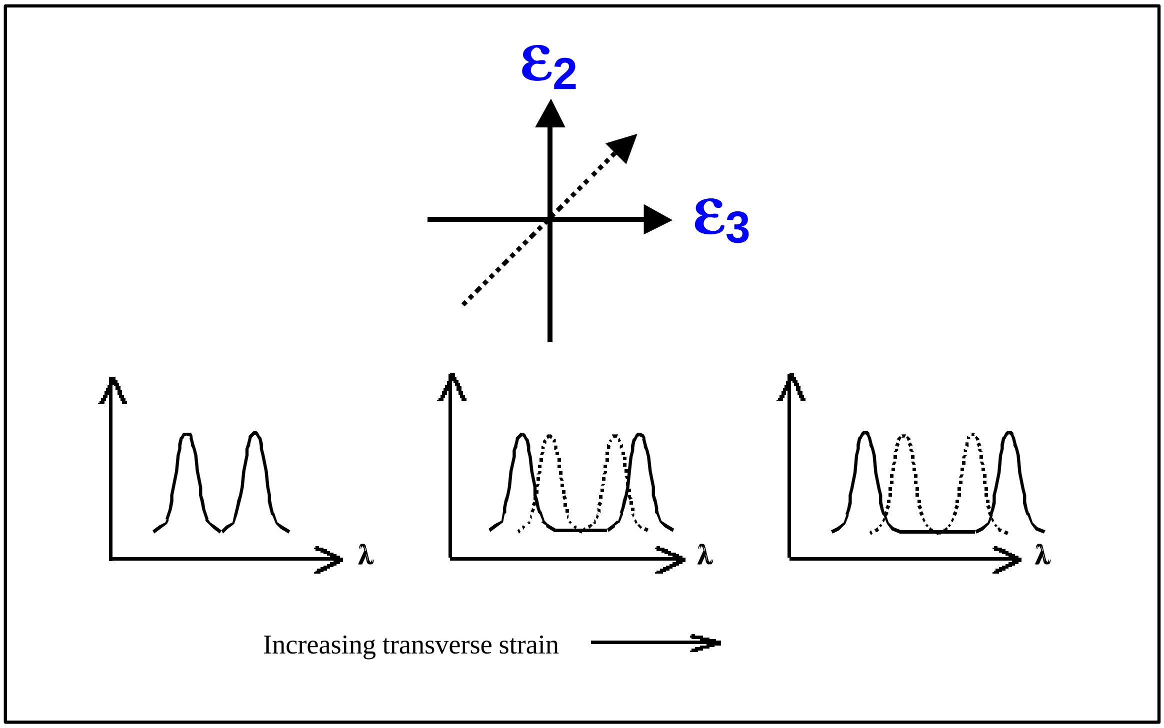

Figure 4. Spectral response of a multiaxis sensor under transverse strain. Peak separations occur for the two pairs of peaks corresponding to the two polarization axes.

Temperature has the same effect on the sensor as axial strain, due to thermal expansion (Figure 5.) Again, this spectral information results in quantifiable measurements of temperature change.

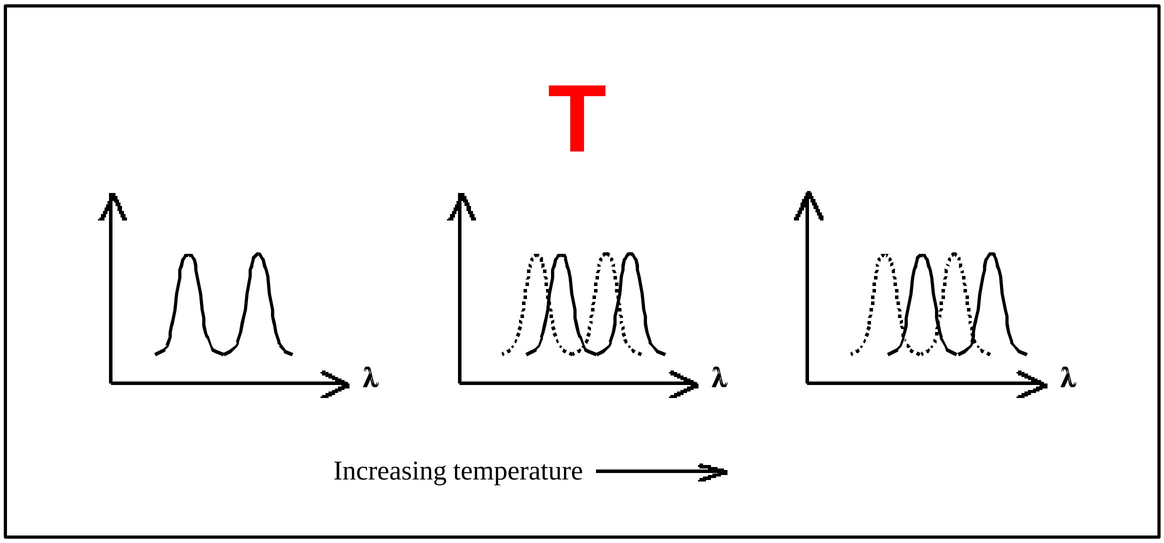

Figure 5. Spectral response of a multiaxis sensor under temperature change. Peak shifts occur for the two pairs of peaks corresponding to the two polarization axes.

While this sensor is still under development, Blue Road Research has made many of these sensors available for beta testing and plans to commercially introduce two axis strain sensors and systems in 1998.

2. ADVANTAGES OF FIBER SENSORS

Fiber strain sensors have many advantages over traditional electrical strain gauges. Some of these advantages include:

- EMI resistance	Fiber sensors are virtually unaffected by electromagnetic interference.
- Much less intrusive size	Uncoated sensors have diameters of 125 μm, with coated (polyimide, for example) diameters of 150 μm – ideal sizes for embedding into metals and composites.
- Higher temperature capability	Upper range of 400°C to 650°C.
- Greater multiplexing potential	Several fiber sensors can be multiplexed along a single fiber line with multiple lines connected to a single demodulator.
- Longer distances	Being fiber optic based, these sensors can be demodulated up to several kilometers from the sensors via standard telecom fiber optic cable.
- Greater resistance to corrosion	Because fiber sensors do not use metal, they are less susceptible to corrosion.

3. COST OF FIBER GRATING SENSORS

The current (February 1998) cost of fiber grating sensors in quantities of 10's is $150 for single parameter sensors and $550 for multi-parameter sensors. For quantities of 100's, these costs drop to approximately $100 and $300 for the single and multi-parameter sensors, respectively. A target cost for the mass production of these sensors has been estimated at $20 and $50, respectively. This target cost along with the many advantages of fiber sensors makes them a strong choice for smart structure applications.

4. DEMODULATION METHODS

One possible demodulation method for the multiaxis sensor is shown in Figure 6[2]. Here two broadband ELED (edge light emitting diode) lightsources are connected to a WDM and then to a 3dB beamsplitter. The combined waveform then goes into the multiaxis grating sensor which reflects four spectral peaks. These peaks are then directed into a PC controlled optical spectrum analyzer where the spectral data is converted to strain values. Figures 7 and 8 show data taken with such a setup for transverse and axial loading.

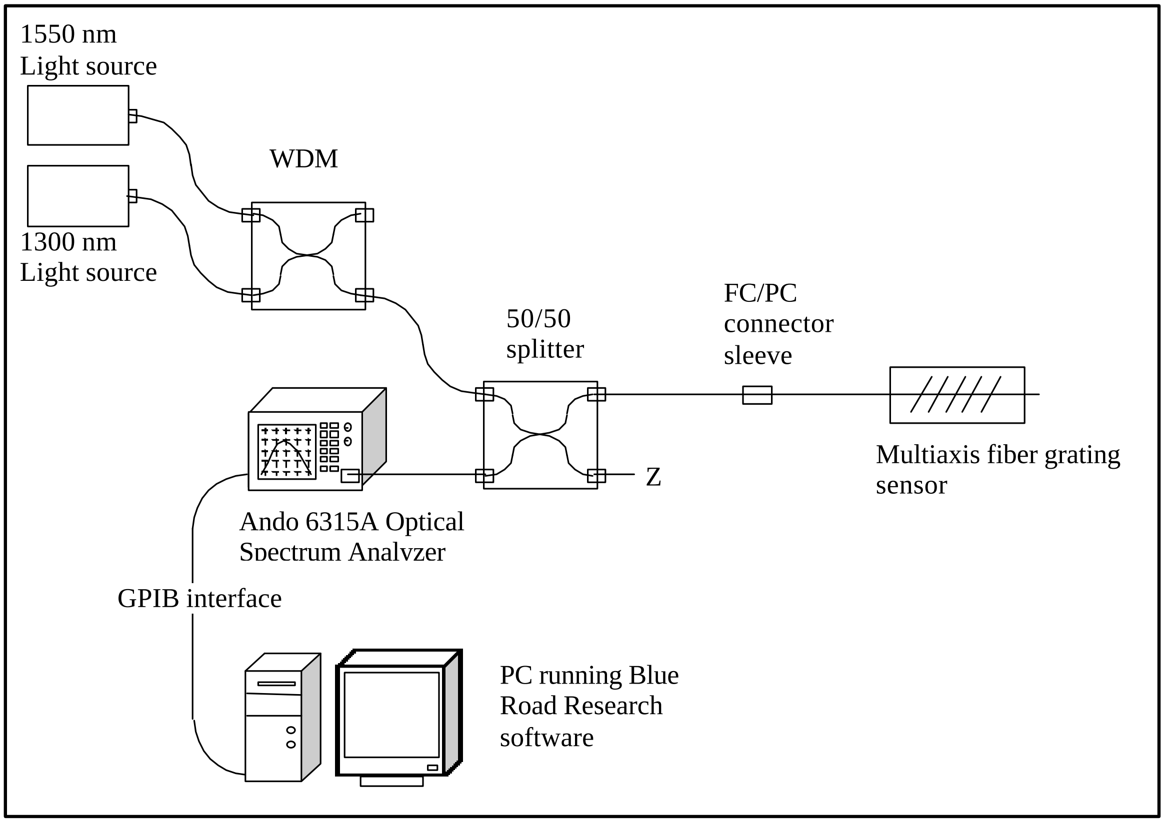

Figure 6. Demodulation setup for multiaxis strain sensor.

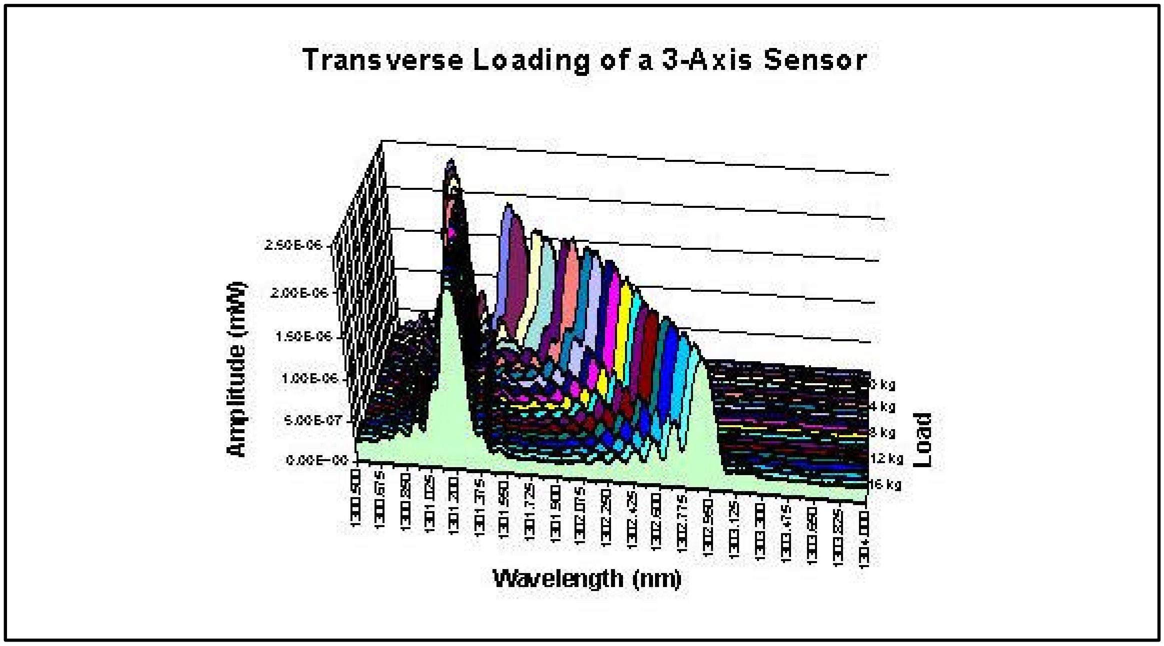

Figure 7. Blue Road Research data on transverse loading of a multiaxis strain sensor. Note the peak separation vs. transverse load.

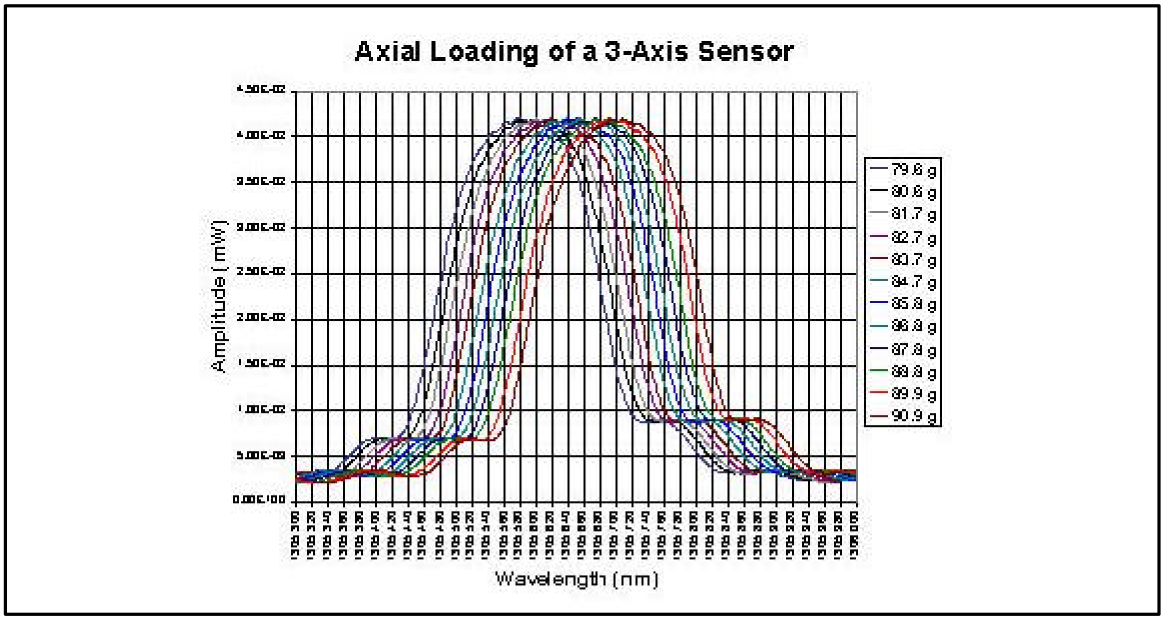

Figure 8. Blue Road Research data on axial loading of a multiaxis strain sensor. Note the peak shift vs. axial load.

Another demodulation system is shown in Figure 9. This system, using a chirped fiber grating as a spectral filter can operate at high speeds up to 3 MHz[3]. This system can demodulate single parameter sensors such as strain or temperature. Blue Road Research plans to have this system available commercially in mid 1998.

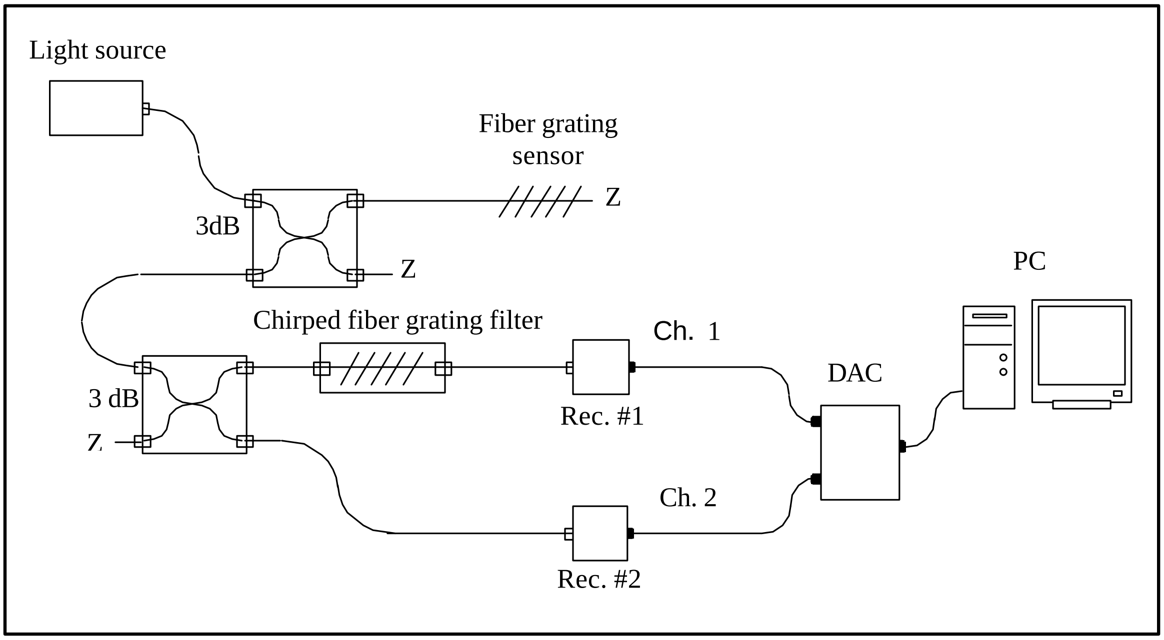

Figure 9. High speed demodulation system for an axial strain or temperature sensor. Speeds up to 3 MHz can be achieved with this system.

5. APPLICATIONS OF FIBER GRATING STRAIN SENSOR SYSTEMS

This section describes several smart structure applications of fiber grating strain sensor systems for civil structures and traffic monitoring/control. One system to support these applications is a load cell with embedded distributed transverse strain sensors (Figure 10.) This load cell has the capability to measure transverse strains and strain gradients[2]. A similar system is shown in Figure 11. This “smart” washer is comprised of embedded distributed transverse strain sensors and is capable of measuring bolt loading, uneven loading, and warn of loosening.

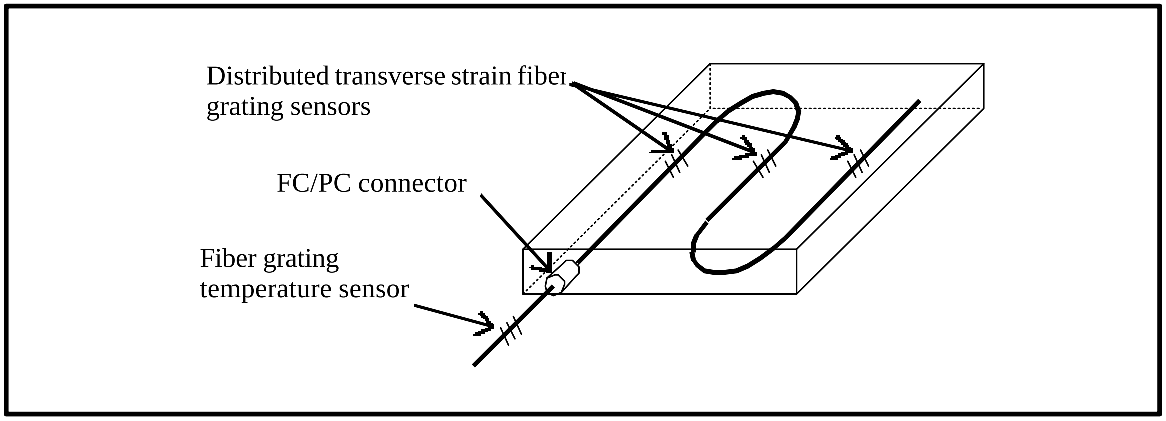

Figure 10. Load cell with embedded distributed transverse strain sensing fiber grating sensors. This setup can also be temperature compensated with a temperature sensor in same fiber line.

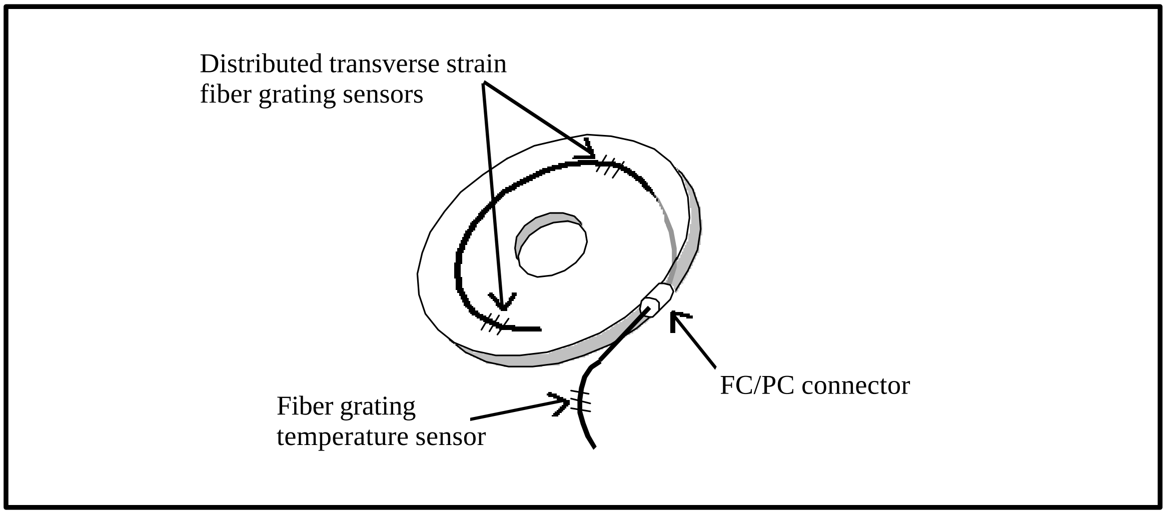

Figure 11. "Smart" washer with embedded distributed transverse strain fiber grating sensors. Capable of quantifying bolt loading or warn of bolt loosening. Can also be temperature compensated with temperature sensor in same fiber line.

The first examples of civil structure applications are bridges. Figure 12 shows a suspension bridge where fiber grating strain sensors are employed to measure the tension in the cables. A drawbridge is also shown in Figure 12 where fiber grating load cells are used to measure the loading and the balance of the deck.

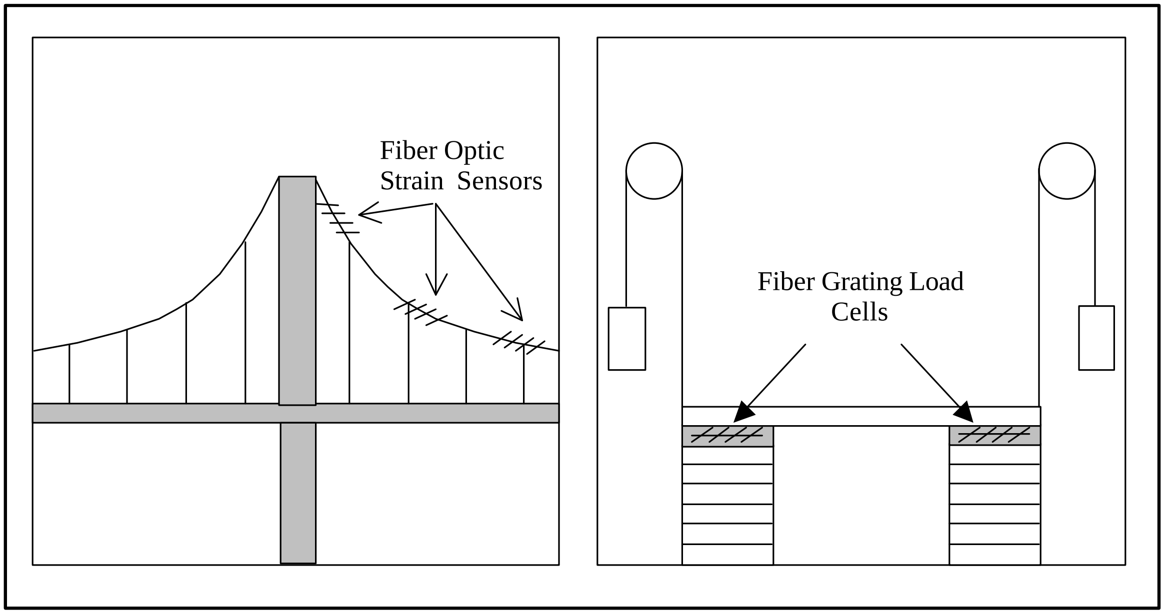

Figure 12. Fiber grating strain sensors to monitor tension in suspension bridge cables and loading and balance in drawbridges.

Scouring is a problem for many bridges and other structures with underwater supports in high current areas. Figure 13 shows two methods of monitoring scouring with fiber strain sensors. The first example on the left consists of a flexible rod which is buried close to the underwater support. Embedded into this rod is an axial strain sensor. As the rod is unburied, it will flex in the current and an axial strain will be measured. As more of the rod is exposed, it will flex more, thus creating more axial strain and indicating the severity of the scouring. The second case on the right uses fiber grating load cells with embedded transverse strain sensors. As the soil is scoured away from the footing, the balance and load distribution will change and will be measured by the load cells.

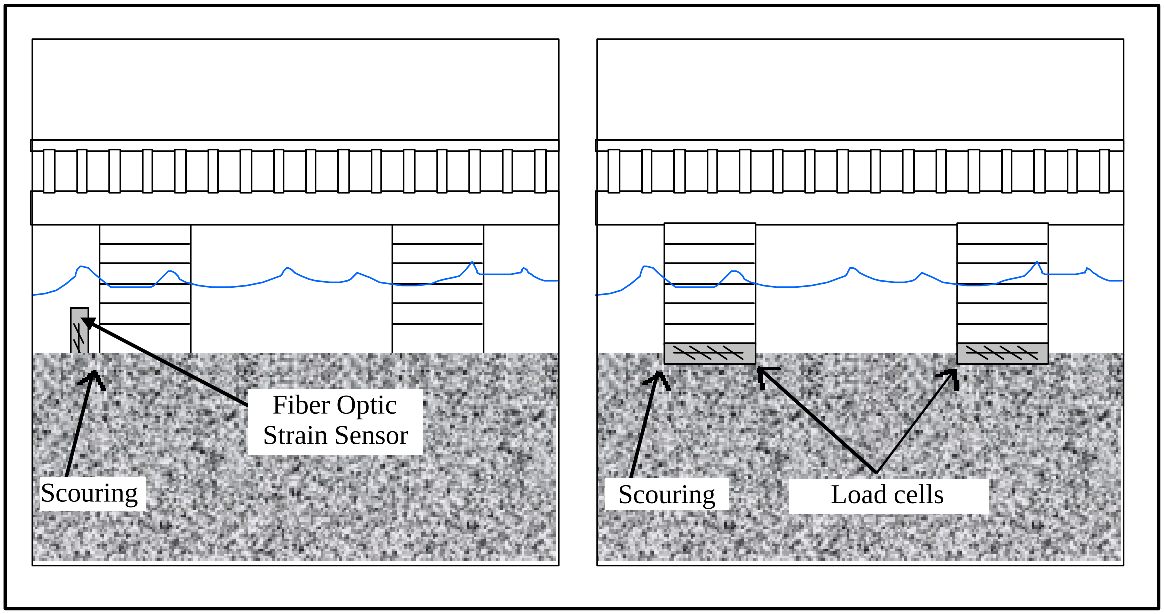

Figure 13. Monitoring bridge scouring with flexible rod containing embedded axial strain sensor which bends in the current as the rod is unburied (left.) Scouring sensor based on load cells to monitor change of loading in footings (right.)

Further examples of fiber sensors being used in civil applications are tunnels and retaining wall anchors. In Figure 14, distributed fiber grating strain sensors are used to monitor tunnel supports. Distributed sensors can also be used to monitor retaining wall anchors. As the soil shifts, or the anchor slips, these sensors can detect an increase or decrease in the load on the anchor indicating the health of the wall.

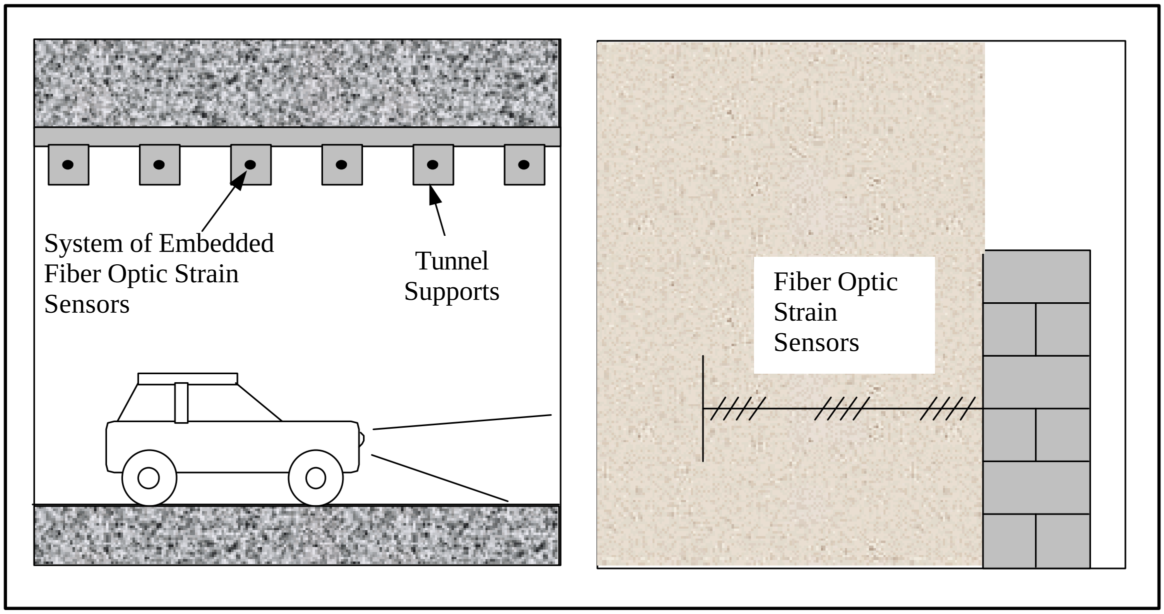

Figure 14. Monitoring tunnel supports with distributed fiber grating strain sensors (left.) Monitoring retaining wall anchor with strain sensors (right.)

Fiber strain sensors can also be used for environmental detection such as ice on roadways. Figure 15 shows a fiber grating ice sensor. This sensor, in the shape of a U-channel, is embedded into the roadway. At the bottom of the channel is a transverse strain sensor. If the channel is empty or full of water and a vehicle drives over it, no strain will be transferred to the sensor. However, if a vehicle passes over the sensor which has ice in it, a transverse strain will be transferred to the sensor indicating ice. This sensor could be connected to a warning system to provide accurate warnings to drivers or possibly initiate a de-icing system.

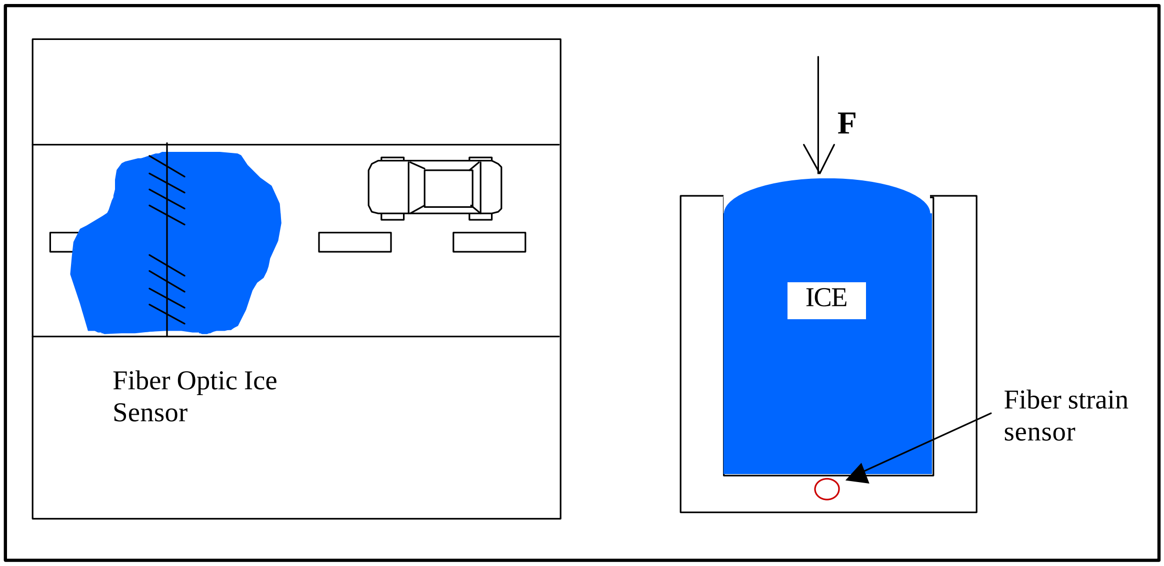

Figure 15. Ice sensor using fiber grating strain sensors (left.) Under icy conditions, vehicles driving over the sensor embedded into the roadway will exert strain on the sensors (right.) Under non-icy conditions, no strain is transferred to the sensors.

The final set of application examples presented here is traffic monitoring and control. Being small and unobtrusive as well as resistant to corrosion, fiber grating sensors are ideal for embedding into roadways to replace traditional sensors and adding new functionality to traffic monitoring and control systems. Figure 16 shows some examples of this.

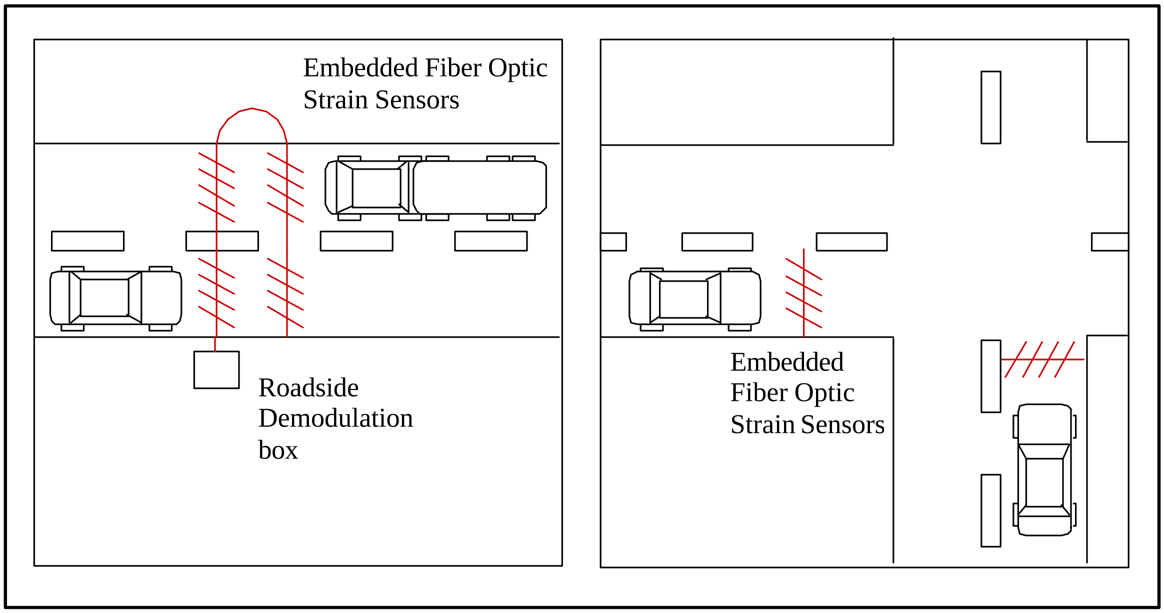

Figure 16. System for monitoring vehicle speeds and weights (left.) System to control traffic flow based on embedded strain sensors (right.) Fiber optic based sensors in these applications have the advantages of being less intrusive, higher resistance to corrosion, and more accurate and reliable.

These embedded sensors could provide weigh-in-motion, speed measurements, and provide traffic control via load cells.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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