

Low Cost, High Speed Fiber Optic Grating Demodulation System for Monitoring Composite Structures

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ABSTRACT

A low-cost high-speed demodulation system based on a fiber grating spectral filter has been developed to support strain and temperature sensing in composite panels. This system has also been used to support high-speed impacts on composite panels. This paper will describe the system, its current state of development, and some of the applications it is supporting.

1. INTRODUCTION

For many applications a low-cost, high-speed demodulation system is required. Blue Road Research investigated a series of approaches including overcoupled couplers [1-3], a miniature Mach-Zehnder [4], and chirped fiber gratings [5]. Trade offs were made between these three designs and the chirped fiber grating approach was selected on the basis of temperature stability, sensitivity, and overall cost. The design allows sensing speeds only limited by the speed of the detection circuit. Current speeds are on the order of 7-10 kHz. A 3MHz version is under development. The 7 kHz speed is intended to support aerospace applications involving fluctuations of airframe structures as well as real time civil structure measurements such as dynamic loading of bridges.

2. BASIC HIGH SPEED FIBER GRATING DEMODULATION SYSTEM

Figure 1 is the optical diagram for the demodulation system which will be introduced commercially in the second quarter of 1998 by Blue Road Research.

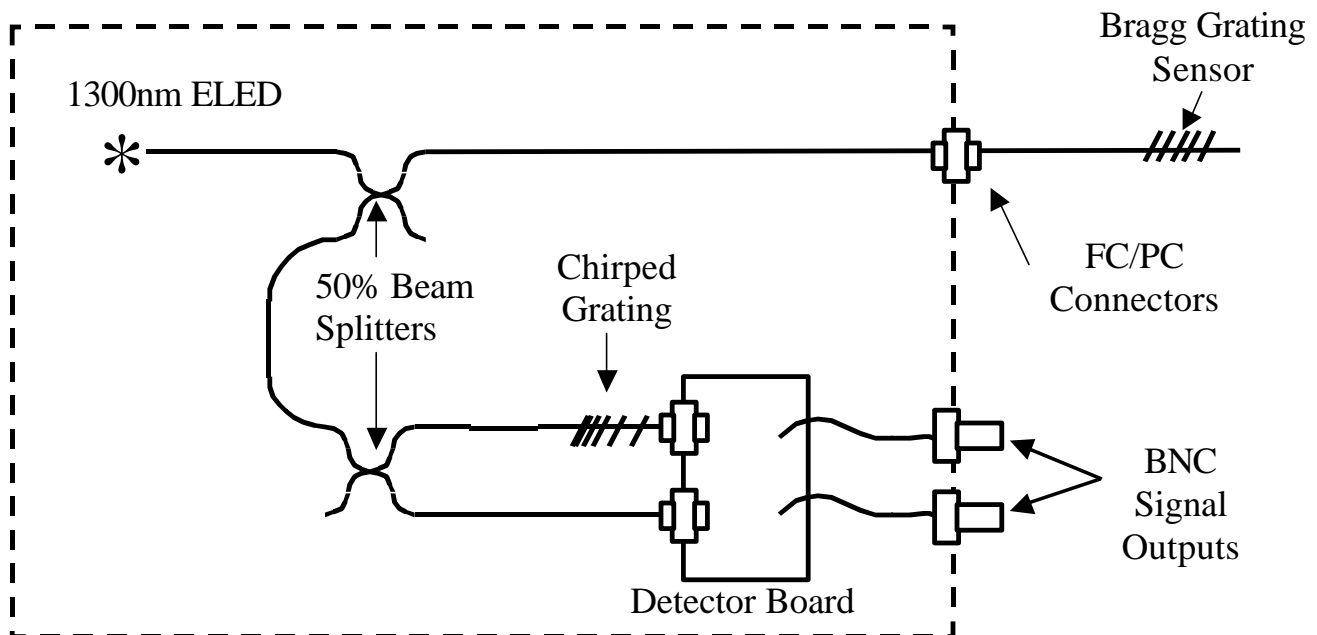


Figure 1: Optical Schematic for demodulation of a Bragg grating sensor. The dashed line indicates components within the demodulator box.

An Edge Light Emitting Diode (ELED) couples light into a single mode fiber and through a 50% beam splitter. Half of the light is guided out the FC port on the front of the box to a Bragg grating sensor. The sensor acts as a strain or temperature transducer and reflects a very small spectral band (or peak) back towards the box but allows most of the optical power to pass through. This reflected peak travels back into the box, and through two beam splitters. Half of the power at the second beam splitter is collected by a fast detector while the other half first goes through a chirped fiber grating and then is detected by a matched detector. The chirped grating truncates the signal in such a way that the ratio of the two output signals is linearly proportional to the strain or change in temperature.

Figure 2 is a typical chirped grating curve set captured with an Ando AQ-6315A optical spectrum analyzer. It contains curves of the ELED (top curve), direct output of the chirped fiber grating (bottom curve) and a normalized version of the chirped grating (center curve). Normalization is necessary because the shape of the light source is not flat and induces nonlinearities into the direct output curve for the chirped grating.

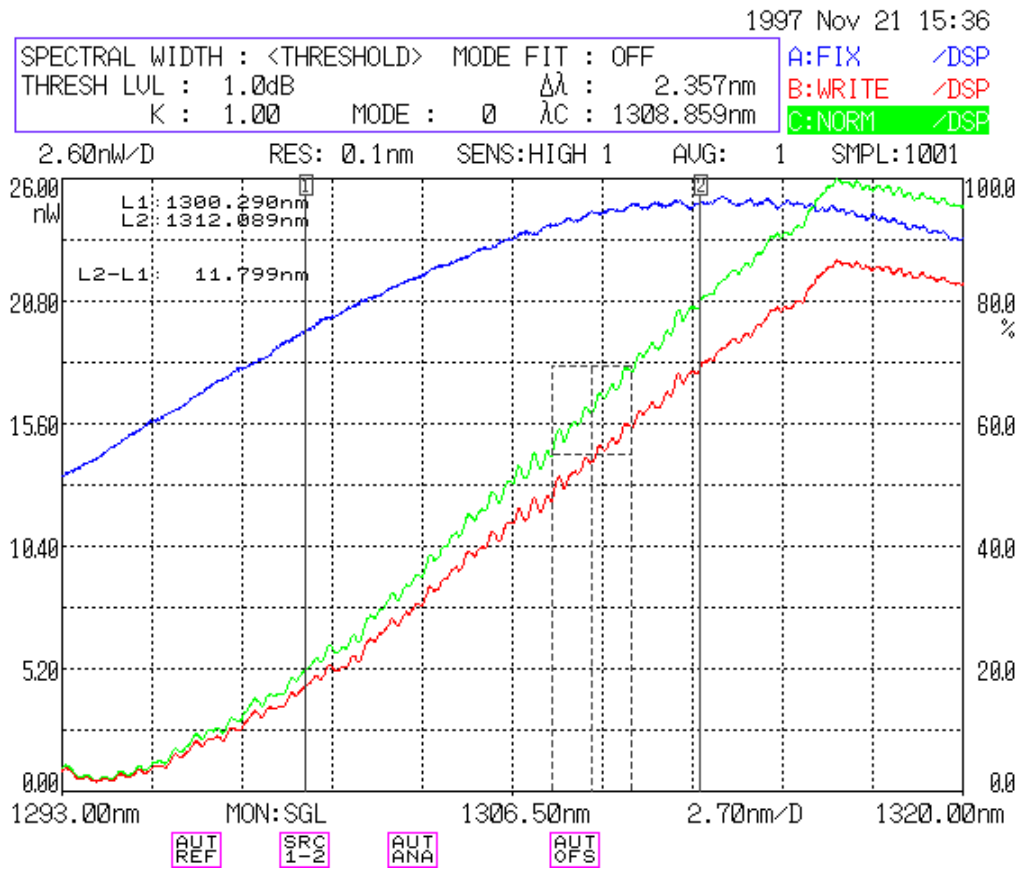


Figure 2: Typical curve set for a chirped fiber grating. The top curve is the light from the ELED that enters the chirped fiber grating. The bottom curve is the light that exits the chirped grating. The center curve is the normalized version, which removes the ELED nonlinearities.

The slope of the normalized curve is directly calculated from the curve as the rise in percent (the standard calibration range is from 20% to 80%) over the run in nanometers. For this case, it is $.60 / 11.799\text{nm}$, or $.0509 / \text{nm}$ change. This slope is valid from about the 10% – 90% range which corresponds to approximately 16 nm or 16000 μe . Temperature sensing is limited by the properties of the fiber and coatings to about 400°C.

An inspection of the normalized curve shown in Figure 2 shows that although the trend is quite linear, there is some fine structure which makes an exact pinpointing of strain difficult. This structure would be very troublesome if the reflection back from the sensor was an infinitely thin spike. However, the reflected peaks from test gratings have a width of about 0.2 nm FWHM. This induces some averaging of the fine structure, which improves results. Current data indicates that

resolution is currently limited by this structure to $\pm 150 \mu\epsilon$ or $\pm 15^\circ\text{C}$ full scale. It is expected that sensors with wider reflection spectra in the range of 0.5 nm to 1 nm FWHM will improve this accuracy.

Target pricing for the demodulator system is about \$5,000 US.

3. OPERATIONAL PROCEDURE

The fast demodulation box (BRR-3SA) uses a chirped fiber grating to relate strain seen by the sensor to a voltage ratio. Figure 2 shows a typical profile for such a filter. Blue Road Research uses the shape of the filter profile and other internal characteristics to provide the constants later used in the calibration process.

Equations 1 and 2 are the strain and temperature calibration equations for the demodulation box.

$$\epsilon = [\mathbf{R}_m - \mathbf{R}] / (\mathbf{R}_0 \mathbf{m} \beta \lambda) + \epsilon \tag{1}$$

$$\mathbf{T} = [\mathbf{R}_m - \mathbf{R}] / (\mathbf{R}_0 \mathbf{m} \xi \lambda) + \mathbf{T}_0 \tag{2}$$

Variables for the equations above are:

R	The ratio of the two output voltages during strain or temperature measurement.
R₀	Ratio corresponding to “zero” or starting state for the sensor
R_m	The maximum intensity through the chirped fiber grating filter
M	The slope of the linear region in the chirped fiber grating filter
β	The elasto-optic coefficient for the fiber grating sensor
ξ	The thermo-optic coefficient for the fiber grating sensor
λ	Center wavelength of the ELED

β and ξ are constants for a specific fiber type and change for different fibers. The table below shows different fibers and their corresponding coefficients. Some fibers will vary even more than the ones listed. The standard single axis grating sensors supplied by Blue Road Research are Corning SMF-28 with $\beta=0.769$ and $\xi=7.64 \times 10^{-6}$ ($1/^\circ\text{C}$). Care should be taken to be certain of the fiber sensor type before using these constants.

Fiber	β	ξ ($1/^\circ\text{C}$)
Corning SMF-28	0.769	7.64×10^{-6}
3M [6]	0.790	6.3×10^{-6}
Fujikura	0.769	6.45×10^{-6}

R is the sensor output, and R₀ must be measured once for each sensor but everything else is constant for each demodulator.

4. TEST RESULTS

Blue Road Research tested two different fiber grating sensors using the setup shown in Figure 3.

The detectors in the BRR-3SA have enough gain to allow the extra 6 dB loss incurred from this test setup. The spectrometer directly measures the wavelength shift induced from straining the sensor with hanging weights (not shown) while the BRR-3SA gives the same information as a ratio of the two output voltages. The following graph (Figure 4) shows typical results. The maximum full-scale error from the 4 separate tests was 1.92%.

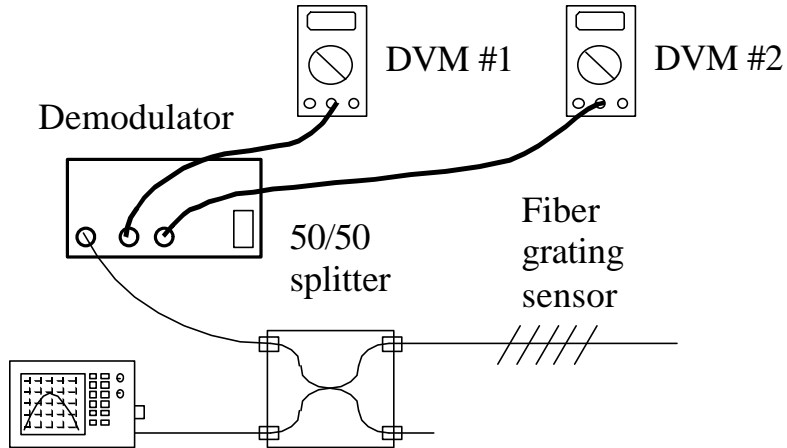


Figure 3: Correlation setup for simultaneously using the fast fiber grating demodulator (BRR-3SA) and an Ando 6513A Optical Spectrum Analyzer.

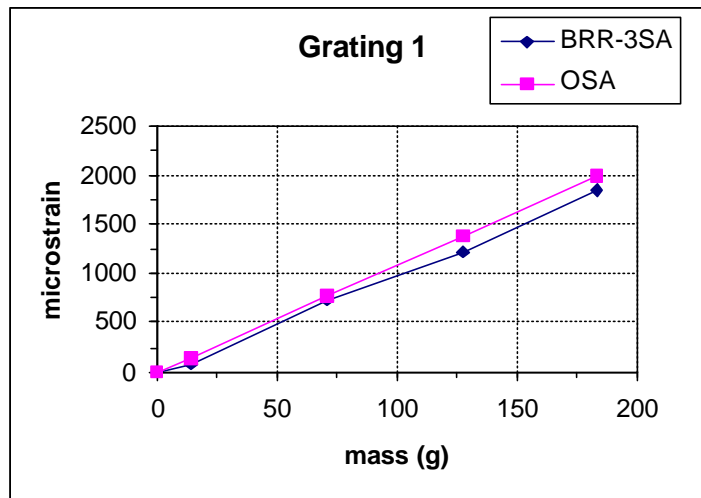


Figure 4: Bragg grating sensor # 1.

5. APPLICATIONS

The fast demodulation system described herein has already been used in several applications. It has been used to measure strain in a composite panel during impact testing and also for monitoring strain levels in a composite utility pole. Figure 5 shows the results of testing a panel measuring 60 cm by 30 cm with drop tests using a 20 kg weight dropped from heights up to 7m. The panel contained an embedded fiber grating sensor located near the surface of the panel approximately 1.6 mm below the surface being struck. For comparison, a resistive foil gauge was located on the opposite side of the panel and an accelerometer on the 20 kg chisel.

Panel 2 - 12 inch drop test

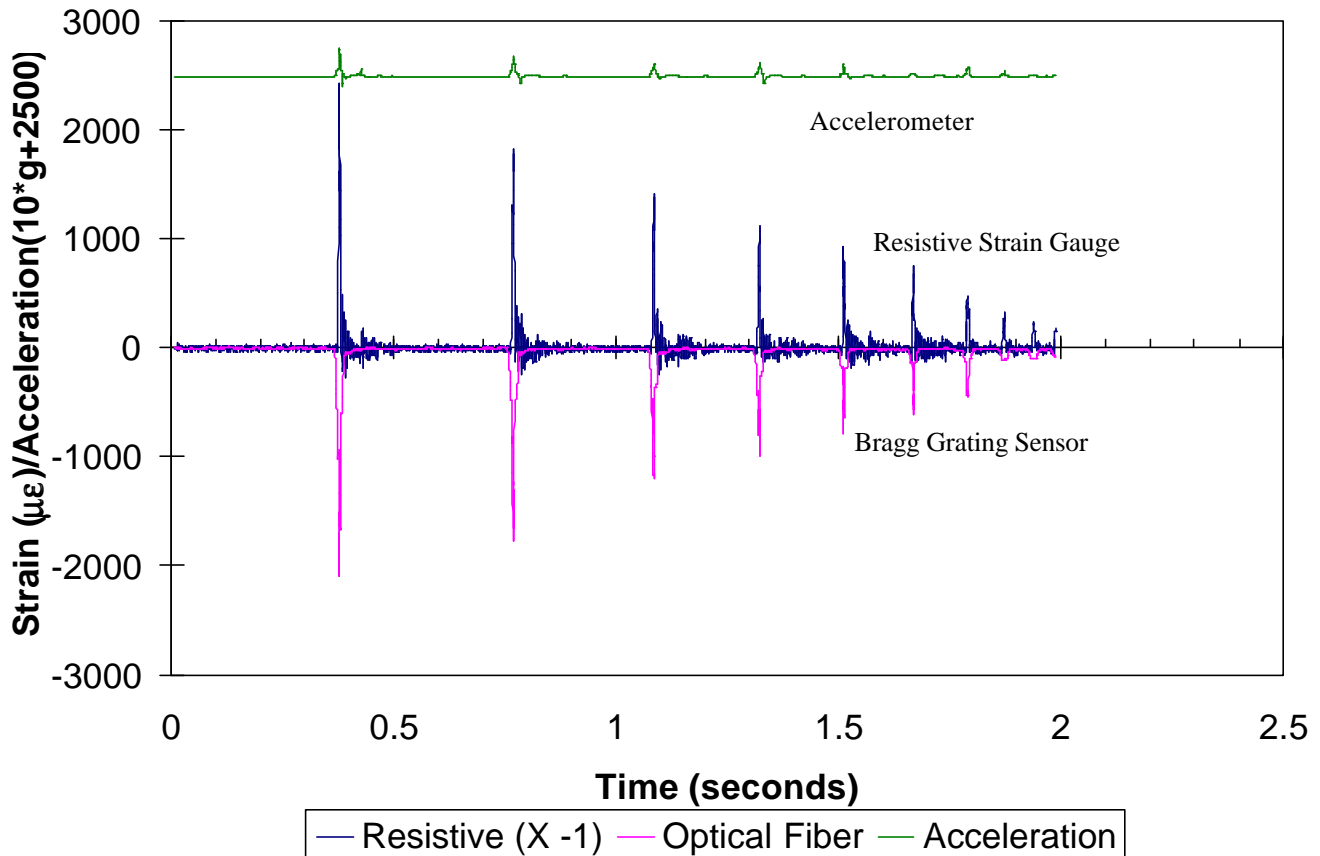


Figure 5: Drop test results using several types of sensors. The fast demodulation system was used in these tests.

Figure 6 shows a composite panel similar to the one used in the impact test. The panel was placed at the bottom of a drop tower and a 20 kg chisel was dropped repeatedly from various heights.



Figure 6: Composite panels with embedded grating sensors were used in drop tests (see Figure 6) and three point bend tests (shown here).

Figure 7 shows a composite utility pole under load conditions. The fast demodulation system was used to record the strain levels via embedded fiber grating sensors at various points on the pole before, during and after failure of the pole.



Figure 7: A 60 ft fiberglass utility pole under bend loading of approximately 6,000 lbs.

6. CONCLUSION

Many exciting areas of application exist for this new demodulation system. It is useful for monitoring civil structures such as bridges, roads, buildings, tunnels, dams and retaining walls. Some aerospace applications would include real-time monitoring of space structures, vehicle skins, and damage detection. These sensors can be imbedded in both composite and metal materials and allow a “cradle to grave” monitoring of parts manufacturing. These sensors can replace standard foil strain sensors in many situations and do not suffer from EMI noise or short lead length restrictions.

7. REFERENCES

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6. 3M Fiber Bragg Gratings Application Note. 2/96