White Paper

Fiber Bragg Grating (FBG) Writing with Excimer Lasers. Fiber Optic Smart Structures on the Rise.

Fiber optical sensors and instruments have moved from research applications to widespread industrial use in structural health monitoring. Due to their inherent advantages, FBG sensors have evolved as the most commonly deployed fiber optical sensors. The quality and longevity of the Bragg grating located inside the fiber core largely depends on UV excimer laser performance characteristics.

Introduction and Overview

Driven by global demand for strain, pressure and temperature monitoring in civil engineering as well as energy production and transmission fiber (figure 1) optical sensor systems have grown as enabling technology overcoming many of the limitations of electrical sensors.

To date, FBG sensors are by far the most commonly used in civil engineering, accounting for 75% of the optical sensors used for structural health monitoring.

Optical sensor market in million USD (Source: LW Venture)

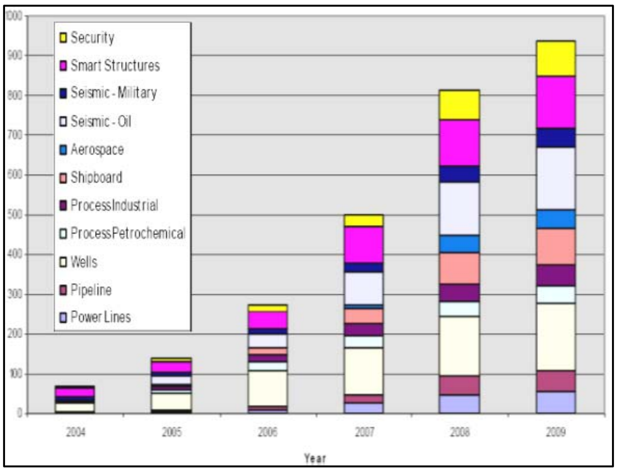

Figure 1

The technical superiority of FBG based-sensor systems over electrical sensor technologies consists of high sensor count, long strain range and low weight plus, they are chemically inert and not influenced by electromagnetic interference or harsh environment.

FBG sensors are regarded as the most mature grating-based sensors and have already been widely used. An FBG sensor reflects a portion of the incoming light of a particular wavelength, called Bragg wavelength, and leaves the rest of the incoming light pass as shown in figure 2.

The wavelength of light reflected by an FBG is determined by the frequency of the refractive index perturbations in the fiber core

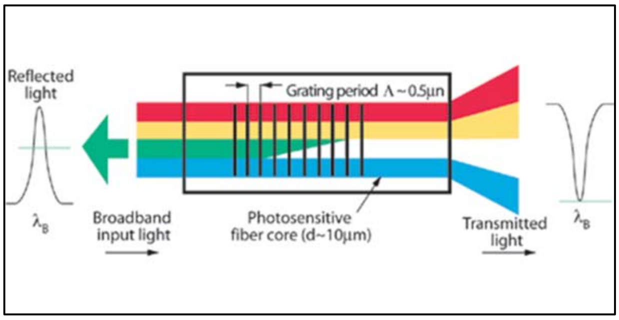

Figure 2

The Bragg wavelength is defined by the fiber refractive index and grating pitch, which are affected by the external environment changes, such as temperature, strain, vibration and other parameters. All these changes are reflected on the Bragg wavelength shift.

Therefore, by monitoring the Bragg wavelength shift, several measurands can be monitored using FBG sensors. Since each sensor grating can have its own grating period e.g. Bragg wavelength, multi point sensing using one fiber of many kilometers in length is possible.

Current interrogation technology is capable of multiplexing up to hundreds of FBG strain sensors and of monitoring them remotely. The principle set up of an FBG sensor system including broad band light source (e.g. a laser diode) and reflective signal recording is illustrated in figure 3.

The Bragg wavelengths of neighboring sensor FBGs are typically separated by a few nanometers to avoid spectral overlap during temperature or strain induced peak shifts.

Multiplexed fiber Bragg grating array for temperature and strain sensing

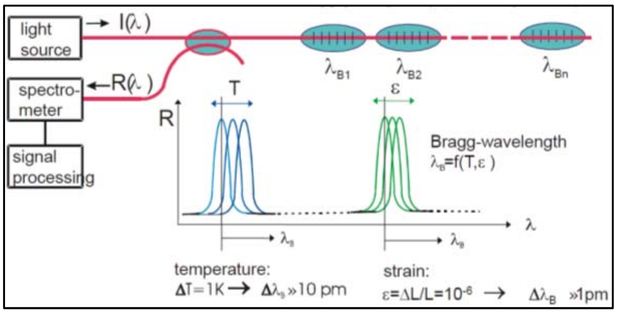

Figure 3

With the rapid development in the past few years, FBG sensors have been targeted as the major leading technology in contrast to other competing fiber optic sensor technologies. Besides its wavelength multiplexing capability, FBG sensors have the advantages of low cost, compact size, and good linearity.
The grating length is usually in the order of 10 mm. The resolution is dependent on the wavelength interrogator, which is currently up to 1 pm, corresponding to 1 με for strain measurement and 0.1 °C for temperature sensing.

The fiber into which FBGs are recorded is tiny, just 0.15mm or so in diameter. The means that many sensors can be applied to a structure with very little intrusion.
Uniquely, a fiber sensor array can be embedded inside a composite to monitor internal strain, temperature and damage with no effect on the structural performance of the composite.

Carbon fiber reinforced polymer with embedded FBG sensor (Source: Daimler)

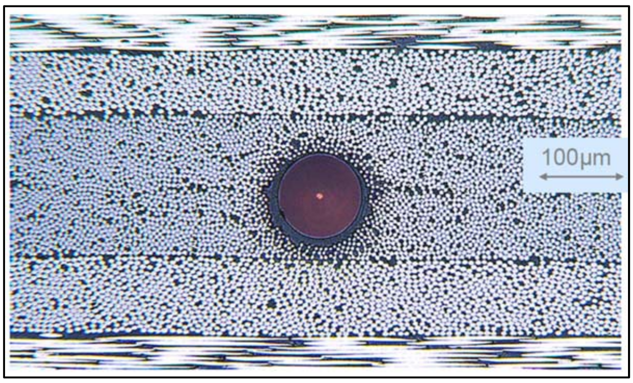

Figure 4

In practice, like living organisms sensitive to subtle changes in the environment, buildings, bridges or dams can be equipped to sense and react to their surroundings by means of hair-thin glass fiber sensors embedded in structural materials and capable of carrying information and measuring changes in stress and other environmental factors. Data is collected and transmitted to a central location, where the findings are assessed and damage corrected.

The civil engineering and infrastructure industry is one of the largest users of optical fibre sensing systems, not surprising given that many of the key advantages of optical fibre sensing lend themselves perfectly well to the requirements of long-term monitoring of distributed sensors over large structures. The cost of a fibre optic sensing system, in which hundreds of locations can be simultaneously monitored with one single instrument, provides sufficient benefit compared with more complex, electrical technologies.
Remote capabilities of optical fibre sensing are also of huge value to very large structures such as bridges, dams and tunnels, in which the sensing system can extend over many kilometres without need for signal amplification and without any of the undesirable down-lead effects associated with many similar electrical technologies.

Schematic view of bridge strain and load sensing

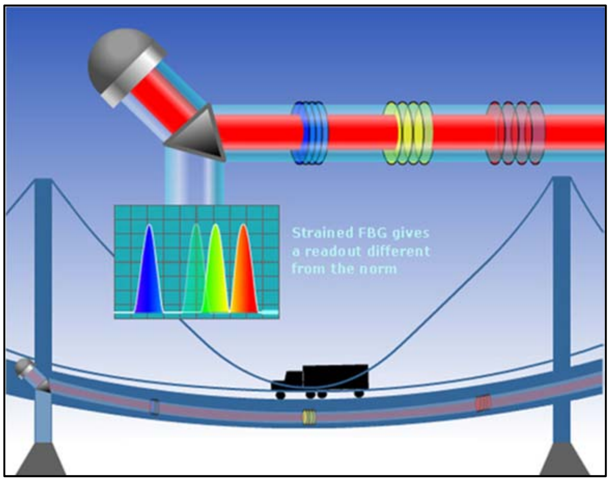

Figure 5

Today hundreds of public buildings, bridges, dams, Intelligent sensing and structural health monitoring as an essential part of infrastructure design, at a fraction of the capital cost of construction, will be key to developing 21st century “high-tech” civil engineering structures.

Writing FBGs using a Phase Mask

The excimer laser is by far the most powerful source of UV laser light, and so can create FBGs within seconds using the standard phase mask approach.

The common method in FBG research and production is phase-mask writing using dedicated 193nm or 248nm excimer laser models with increased coherence. This is largely due to its high mechanical and optical stability as opposed to e.g. an interferometric FBG writing optical architecture.

When illuminated with the laser beam, the phase-mask generates a regular interference pattern. Enhanced spatial coherence length of the excimer laser provides good contrast behind the mask which is typically placed in a distance of 100µm to 200µm from the fiber core.

Phase mask writing using a static, large beam and a scanning, small beam

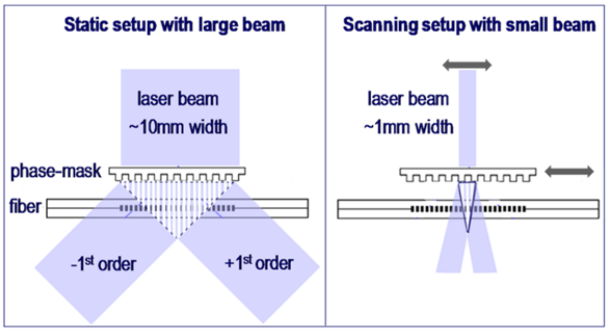

Figure 6

The fiber-phase mask assembly can be illuminated by a large and static beam covering the entire FBG area of typically 10mm length. Due to the required large field size, high-coherence excimer lasers with about 100 mJpulse energy are ideal for the static beam approach

The appropriate laser model for large beam FBG writing is the dedicated BraggStar M version which has been introduced to the market at Photonics West in January 2011. The BraggStar M, shown in figure 7, has a small footprint of 0.5m^2 and delivers high pulse energy of up to 140mJ with repetition rates of up to 100Hz. Spatial coherence-length is 800µm, FHWM.

This laser model can potentially be used for parallel writing of multiple gratings by beam splitting

The dedicated resonator design of the Braggstar M model provides long spatial coherence to support all phase mask writing configurations.

High-coherence laser BraggStar M for large area FBG manufacturing

Figure 7

Alternatively, a smaller beam of typically 1mm beam width which is then scanned relatively to the phase mask in order to build up the desired FBG structure can be employed. The scanning setup provides higher flexibility as to writing irregular grating profiles as in the case of chirped gratings.

Such illumination is best achieved by the high-coherence, low pulse energy model BraggStar Industrial.

Typical excimer laser parameters used in phase mask writing

Phase-Mask Method	Beam size on fiber	Fluence on fiber	Pulse Frequency
Static, large beam	10mm x 1mm	250mJ/cm²	50Hz
Scanning, small beam	1mm x 1mm	250mJ/cm²	200Hz

Figure 7

Phase Mask Writing in Industry and Research

A clean room FBG manufacturing facility at Technica SA in Beijing, China is shown in figure 8.

This is one of about 50 worldwide producers of FBG components for use in fiber optic sensing, telecommunications, and various other industries.

In the background the latest Coherent Bragg Star Industrial model is discernible providing a repetition rate of up to 1kHz for fast and reliable 248nm mass production of fiber bragg gratings using the phase mask method.

Industrial FBG manufacturing facility based on BraggStar Industrial series (Source: Technica SA)

Figure 8

As shown in figure 9, the optical setup for phase mask FBG writing is rather simple in optical design and in generally consists of one or two deflection mirrors, a cylinder lens for short axis focusing, aperture and phase mask.

Always the short axis which has the lower divergence (~0.2mrad, FWHM) and correspondingly higher spatial coherence length (~1mm, FWHM) is focused in phase mask writing.

Lab setup for phase mask excimer laser writing of FBGs at Munich Applied University

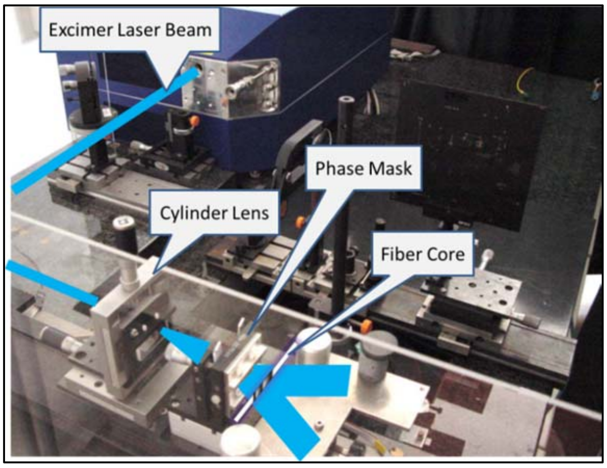

Figure 9

The typical length of the written fiber Bragg grating is about 5 to 10mm with the grating period or pitch in the range of 500nm.

Draw Tower Grating Technology

Figure 10 illustrates the process of writing FBG gratings directly into the fiber core during its drawing. The input of the process is a photo-sensitive pre-form. By heating the pre-form, the pulling and formation of the fiber will be initiated.

Further downstream in the production process, the fiber crosses the optical axis of a line-narrowed, high-temporal coherence 248nm-excimer laser model.

Process of simultaneously drawing the fiber and writing the grating prior *to coating (Source: FBGS International)*

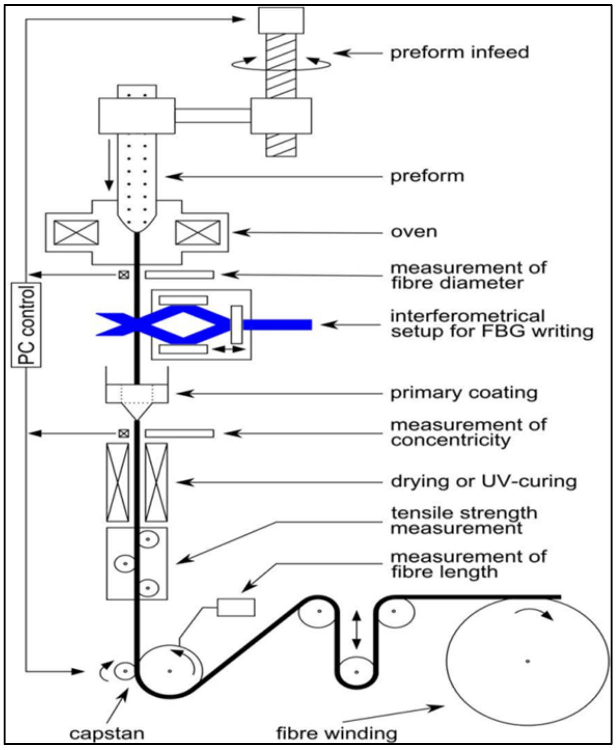

Figure 10

Based on a Talbot interferometer as indicated in figure 10, a grating is written on the fly within a single excimer laser pulse at high fluence.

By means of a pulse selector and by taking into account the draw speed, FBGs can be written on well-determined locations in the moving fiber.

After the grating has been written the fiber is coated by entering a liquid coating reservoir, followed by an UV-curing of the coating.

Finally the location of the FBG is marked automatically and the fibre is reeled on a drum. Draw Tower Grating technology allows to produce spliceless grating chains with a high number of sensor elements.

Another advantage of simultaneously drawing the fiber and writing the grating is the resulting high mechanical fiber strength.

This is caused by the fact that the coating is applied after the grating is already written. Applying the draw tower grating technology commonly used stripping and recoating process as with standard FBG production facilities is circumvented.

Though the short nanosecond pulse duration of the excimer laser enables on the fly writing with high grating accuracy, the exposure has to be done within a single laser pulse.
Accordingly, the applied total fluence or dose is very low and the achieved grating reflectivity is only in the 10 to 20% range.

The Importance of Laser Fluence in FBG Writing

In order to illustrate the behavior of the FBG reflectivity and peak position during the illumination process spectra obtained after a number of excimer laser pulses can be recorded.
This serves to evaluate the required number of pulses at a given fluence in the manufacturing process.
In the example curves depicted in figure 11 saturation of the grating reflectivity at a value of ~85% is achieved after about 70 excimer laser pulses.

Increase of grating strength with number of applied excimer laser pulses at the same fluence (Roth, FHM)

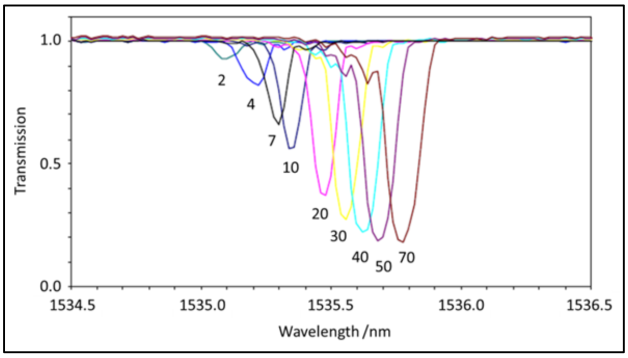

Figure 11

The FBG reflectivity behavior during the process is monitored using a broad band light source and a spectrum analyzer.

That the exposure fluence itself is an important parameter is illustrated by the curves shown in figure 12 below.
Irrespective of the number of applied laser pulses fluence may limit the ultimate fiber bragg grating strength which can be achieved, given that all other experimental conditions are the same.

Increase of grating strength with increasing dose for exposure fluence levels 100, 200 and 300mJ/cm2 [Exitech]

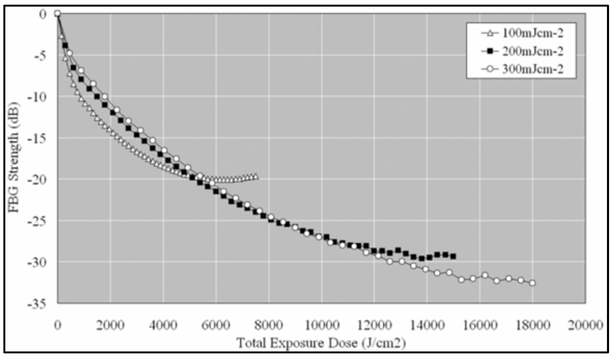

Figure 12

Two fluence related aspects are thus to be considered in fiber bragg grating production as noticable from figure 12: First, there exists a maximum dose at each exposure fluence, beyond which value no increase in the FBG strength is observed, and second, the maximum FBG strength which is reached increases with the exposure fluence and occurs at increasingly higher doses.

Therefore, if a -30dB grating is required, it cannot be obtained using a fluence of 100mJ/cm^2, irrespective of how much dose is supplied. It can only be attained at fluences of 200mJ/cm^2 or 300mJ/cm^2. However, for the 200mJ/cm^2 fluence, it will take around a dose of 2000J/cm^2 more to reach the -30dB grating strength than with the 300mJ/cm^2 fluence.Excimer lasers can easily provide the optimum fluences of several hundred Joules over sufficiently large areas, which apart from their ideal output wavelength constitute a large part of their longstanding success in FBG writing.

FBG Writing Market Outlook

Laser diodes that cost $3000 three decades ago with lifetimes measured in hours now sell for a few dollars in small quantities, have reliability of tens of thousands of hours and are used widely in compact disc players or bar code readers. Optical fibers that cost $20/m three decades ago now cost a few cent per meter with vastly improved optical and mechanical properties. The same holds for integrated optical devices. Also, they will drop dramatically in price in the future while offering ever more sophisticated optical circuits. As these trends continue, the market acceptance for fiber optic sensing will increase and FBG writing with excimer lasers can be expected to assume an ever more prominent position in FBG volume manufacturing.