# All Solid-State Continuous Wave UV Laser for Writing FBGs

**The low noise 230 mW, 266 nm output of the Coherent Azure is well-suited to writing high contrast gratings in fibers made from a variety of different doped glasses.**

## Introduction and Overview

A Fiber Bragg Grating (FBG) is a short length (up to a few cm) of optical fiber in which the refractive index varies sinusoidally along the length of the fiber. When light enters such a fiber, the resultant interference causes a strong reflection at a target wavelength determined by the periodicity length of the FBG. The two principal applications areas for FBGs are in telecommunications and fiber sensing. In telecom for example, a FBG may be used to provide a fixed wavelength for locking a source or detector, a chirped fiber may be used to compensate for dispersion in long-haul applications, or a FBG can be used in some add/drop stages as part of a wavelength division multiplex (WDM) network. In fiber sensing, reflections and transmissions are used to sense ambient changes in the FBG caused by physical strain or variations in temperature. Specific examples include bridges and other large civil engineering projects, as well as so-called "smart structures."

Until now, FBG writing has been dominated by gas lasers, either excimers or frequency-doubled argon ion lasers. But recently, a compact, cost-effective solid-state laser has emerged as a turnkey alternative – a single mode, frequency-quadrupled (266 nm) variant of the diode-pumped solid-state (DPSS) laser. This whitepaper explains how FBGs are created and show test results on FBGs fabricated with this new laser – the Coherent Azure™.

## Background Creating FBGs

FBGs are created by exposing a step indexed, germanosilica fiber to an intense, modulated (striped) pattern of UV laser light, often after hydrogen doping to increase the fiber photosensitivity at the laser wavelength. Absorption of this light in the germanium-doped core causes a permanent change in fiber refractive index. There are three basic techniques presently in use that can produce the required high frequency index modulation with the necessary accuracy: interferometric, phase mask, and projection mask.

In the interferometric method, a single laser beam is split into two components, which are subsequently recombined at the fiber to produce an interference pattern. This requires a laser source with good coherence length, ideally achieved through single longitudinal mode output. One disadvantage of this technique is that the interference fringe spacing and placement is highly sensitive to the optical alignment of the system. Furthermore, maintaining adequate fringe contrast requires high mechanical stability and isolation from ambient vibration. Finally, this approach cannot be used to create variable spaced (chirped) gratings. On the other hand, the interferometric technique is flexible, allowing grating parameters to be changed quickly.

The phase mask approach utilizes a diffraction grating to split a single laser beam into several diffractive orders. Interference between the various orders creates the required pattern in the fiber. The phase mask technique does not have the flexibility of the interferometric method, but it is far less sensitive to vibration and alignment, making it generally more suitable for production environments. Additionally, the use of phase masks enables the production of chirped gratings, which can be very useful for dispersion in long-haul WDM.

The third FBG production approach utilizes a mask projection technique. In this method, a laser beam is homogenized and passed through a mask. This illuminated, striped pattern is then projected at a high reduction ratio on to the fiber. The advantage of mask projection is that it can be used to produce virtually any type of complex periodic or even non-periodic structure. But unlike the other methods, it is difficult to achieve resolutions that produce sub-micron features.

## Existing Laser Sources for FBG Production

Figure 1 shows the photosensitivity of hydrogen-free fiber [1]. The optimum wavelength for photosensitivity in standard Ge-doped telecommunications fibers is in the 240 nm region. Until recently, the only lasers that could deliver the necessary combination of UV power and beam characteristics for FBG production in this wavelength region were the excimer and the frequency-doubled argon ion. While these have enjoyed success they both come with limitations.

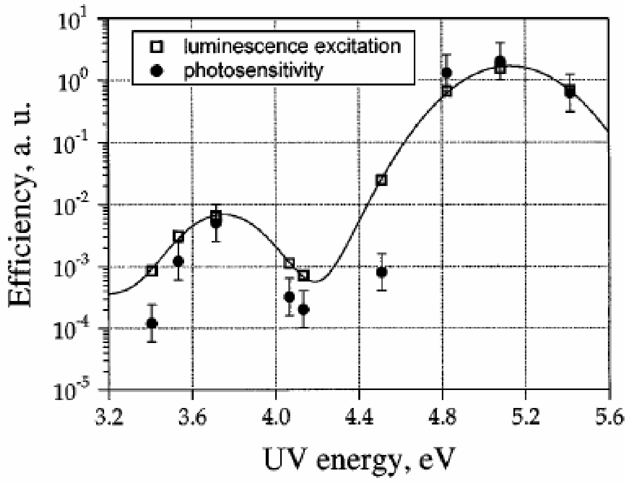


***Figure 1:** Photosensitivity of $H_2$-free Ge-doped fiber (10% mol.) follows the excitation spectrum of the triplet state of germanium oxygen-deficient centers. The solid curve is a fit using the sum of two Gaussians.*

The ion laser offers excellent spatial and temporal coherence, stable output and good beam uniformity. Its primary drawback is low power. This leads to long exposure times (typically 45 minutes), thus requiring careful elimination of ambient vibration, thermal cycling and air currents. Furthermore, the long exposure of the fiber can cause it to become heated itself; this changes its dimensions and can alter grating characteristics.

From a practical standpoint, the ion laser requires 208V/60A, three phase power for just a few watts of output, and most of the input power must be dissipated as waste heat. In addition, frequency doubling of a CW laser is a highly non-linear process that is very intensity sensitive. Thus, even small power changes of the input (488 nm) can cause a dramatic change in the output power at 244 nm.

On the other hand, the excimer laser is by far the most powerful source of UV laser light, and so can create FBGs in seconds instead of minutes. However, the excimer is not a panacea for FBG writing because of its large size, high power consumption and relatively high cost of ownership. Also, excimers tend to produce poor spatial coherent and beam quality, requiring the use of beam modification optics and usually confining their use to phase mask and projection mask methods.

In part because of the limitations of these gas laser sources, FBG manufacturers sometimes modify the basic fiber by hydrogen doping. This increases fiber photosensitivity and broadens the absorption peak allowing longer laser wavelengths to be used. By using $H_2$ doping, grating fabrication has been reported using pulsed copper vapor lasers at 255 nm, 271 nm and 289 nm [2] and using a CW quadrupled Nd:YAG at 266 nm [3]. Both studies showed good grating writing capability at the longer wavelengths.

Building on these results, the Coherent Azure was developed as a turnkey, all solid-state source of CW 266 nm laser light with high coherence (see figure 2). Specifically the Azure is a diode-pumped, solid-state laser operating on a single longitudinal mode that uses an integrated resonant cavity to convert the frequency-doubled 532 nm output to a frequency-quadrupled wavelength of 266 nm. This corresponds to a photon energy of about 4.72 eV. Moreover, the beam pointing stability is very high (±5 µrad/°C) and the Azure also produces a near-perfect $TEM_{00}$ beam profile ($M^2$ <1.3) and a beam waist diameter of 1.05 mm at source.

***Figure 2:** The Coherent Azure is a compact all solid state CW laser with deep UV (266 nm) output.*

Thus, Azure offers all the positive features of ion lasers, namely long coherence, low-noise, and excellent beam quality, but with none of the practical drawbacks. In contrast to ion lasers, the Azure delivers robust, stable operation over a long lifetime and has been deliberately designed to require no user intervention during its planned lifetime. Plus the utility requirements are minimal, namely, a standard power outlet. The Azure is also a field-proven architecture over several years, with some models used in demanding scientific research applications and others employed in the semiconductor industry for high-throughput inspection applications.

Of course, the Azure's operating wavelength of 266 nm is longer than the typically used 248 nm of an excimer laser. Consequently, 266 nm is not ideal for making gratings in hydrogen-free fiber, although 266 nm can still be used with some undoped fibers. However, hydrogen loading is commonly used in FBG manufacture, potentially opening many of these FBG fabrication applications to the Azure.

### Creating FBGs with Azure

The Azure's ability to create FBGs has been extensively tested with various glass types in an independent study at Aston University (Birmingham, UK). The unique properties of Azure, particularly its excellent coherence and output mode stability, mean that it could be used to create FBGs by any of the three methods described above. In the Aston study, a phase mask of uniform period was used. The setup for this study is illustrated schematically in figure 3. The laser power output was initially set to 200 mW and the beam diameter was approximately 1.2 mm at the mask. All hydrogen loading was carried out at 80°C and 220 Bar of pressure.

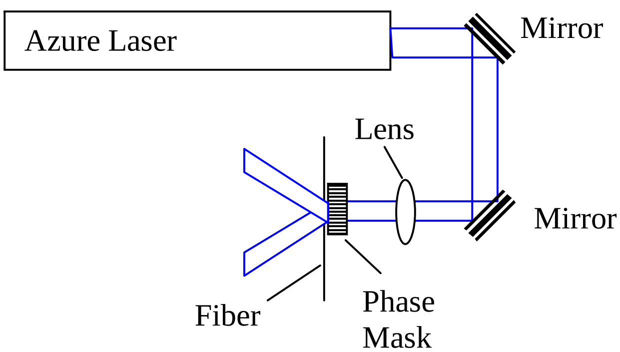


***Figure 3:** Schematic of the grating fabrication arrangement.*

Four different fiber types were investigated:

1. A standard telecommunications fiber: Corning SMF-28

And three photosensitized fibers

2. Fibercore SM-1500, a high-Germanium-doped fiber
3. Fibercore PS-1250/1500, a Boron/Germanium co-doped fiber
4. Fiberlogix Photosensitive fiber, another high-Germanium-doped fiber

### Hydrogen Loaded Fiber

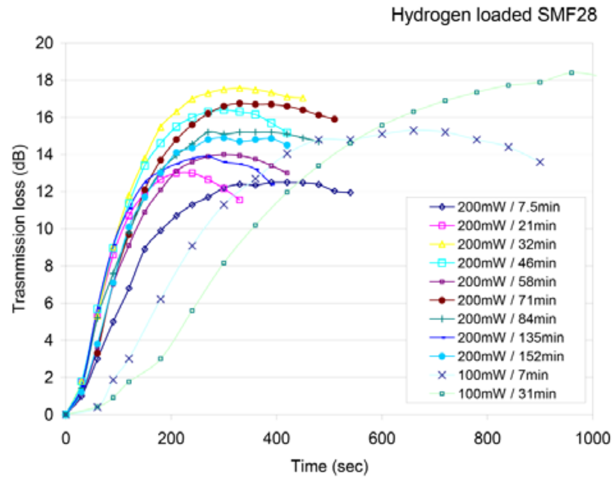


***Figure 4.** Grating growth in hydrogen-loaded SMF28.*

Figure 4 shows the evolution of transmission loss for a number of gratings grown one after another in hydrogen-loaded SMF28 for 200 mW and 100 mW of laser power. At 200 mW laser power, the gratings saturated at a reflectivity of between 95% to 98% after only 200 to 300 seconds exposure. This corresponds to a dn change of ~0.0036 to 0.0045. Even when the laser power was reduced to 100 mW, no decrease in saturated grating transmission loss was observed, although the exposure time to achieve saturation increased to about 800 seconds on average.

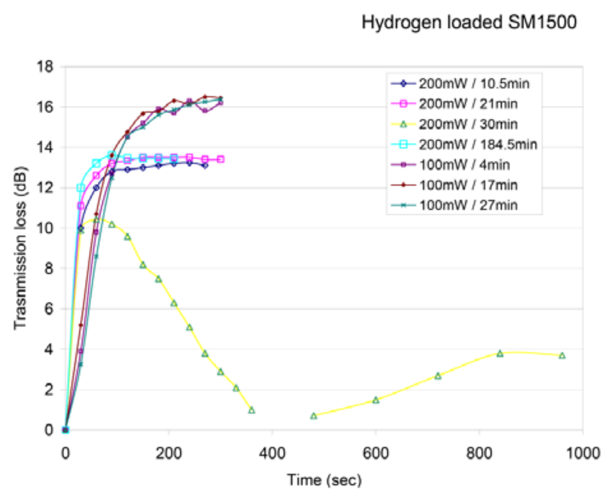


***Figure 5.** Grating growth in hydrogen-loaded SM1500*

Figure 5 shows the grating growth for a number of gratings made in hydrogen-loaded Fibercore SM1500 for 200 mW and 100 mW of laser power. At 200 mW of laser power, the gratings saturated at a reflectivity of 95% to 96% after only 90 seconds of exposure. This corresponds to a dn change of ~ 0.0036 to 0.0038. By reducing the laser power to 100 mW a small increase in grating transmission loss was observed (possibly due to lower self-annealing); simultaneously, the exposure time increased to about 240 seconds on average. The yellow line shows a type-I/IA growth pattern often seen in hydrogen-loaded photosensitive fibers where a different photosensitivity mechanism is observed after the first grating has formed, which creates gratings with slightly different properties. [4]

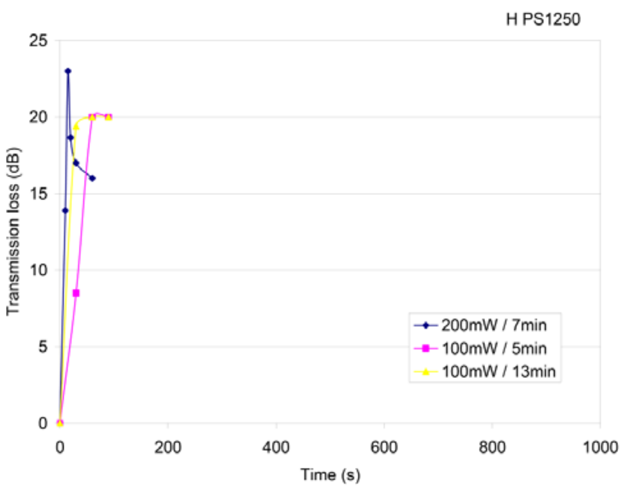


***Figure 6.*** *Grating growth in hydrogen-loaded PS1250*

Figure 6 shows the growth of a number of gratings fabricated in hydrogen-loaded Fibercore PS1250 fiber for 200 mW and 100 mW of laser power. This fiber proved to be extremely photosensitive to the Azure laser; at 200 mW of laser power the transmission losses of the gratings exceeded the measurement capability of the set-up within just 15 seconds. However, from the bandwidth data, the dn change could be estimated at ~0.0053. By reducing the laser power to 100 mW, no decrease in grating transmission loss was observed although the exposure time increased to about ~60 seconds before saturation. It is interesting to note that these results actually exceed the dn values achieved in scanned exposure tests with a 244 nm frequency-doubled ion laser (Coherent FreD) in which dn values of up to 0.001 were recorded.

Figure 7 shows the grating growth for a number of successive exposures in hydrogen-loaded Fiberlogix Photosensitive fiber for 200 mW and 100 mW of laser power. At 200 mW of laser power the gratings saturated at a transmission loss of between 18 dB after 90 seconds exposure. This corresponds to a dn change of ~0.0045. By reducing the laser power to 100 mW a small decrease in grating transmission loss was observed, with transmission losses of 15-16 dB achieved with an exposure time of about 240 seconds.

Again, evidence of some type-I/IA grating growth pattern is seen (blue line).

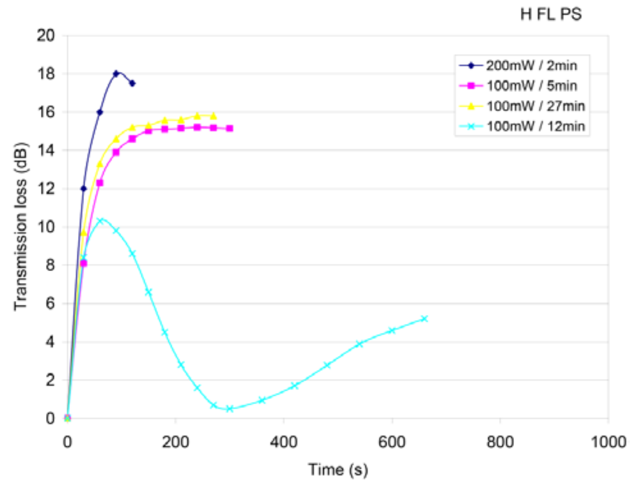


***Figure 7.*** *Grating growth in hydrogen-loaded Fiberlogix PS*

**Non-Hydrogen-Loaded Fiber**

As expected, using non-hydrogen-loaded fiber significantly reduced the photosensitivity of the fibers at 266 nm. However, in the photosensitive fibers small gratings could still be fabricated. Figure 8 summarizes the growth characteristics for the three photosensitive fibers. Type I gratings with transmission losses of between 0.4 dB and 2.6 dB were fabricated. This corresponds to a dn change of ~0.00055 to 0.0014. In addition, Type IIA grating growth behavior was seen for the Fibercore PS1250 and Fiberlogix PS fibers.

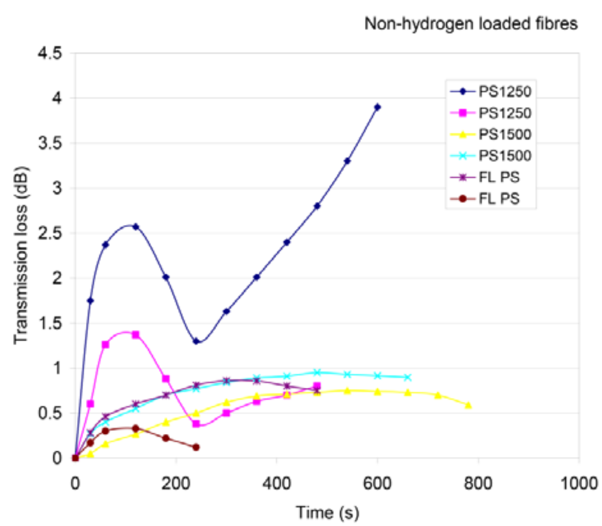


***Figure 8****. Grating growth in non-hydrogen-loaded fibers*

Of course, even when the dn change cannot be increased, an alternative is sometimes to increase the length of the FBG. Calculations of this effect are shown in Figure 9 which plots how the transmission loss of gratings varies with dn for different fiber lengths. These simple calculations show that if a transmission loss of 1 dB is achievable in fiber with a grating of length 1.2 mm, then for a longer grating of 5 mm a transmission loss of ~10.9 dB should be achievable.

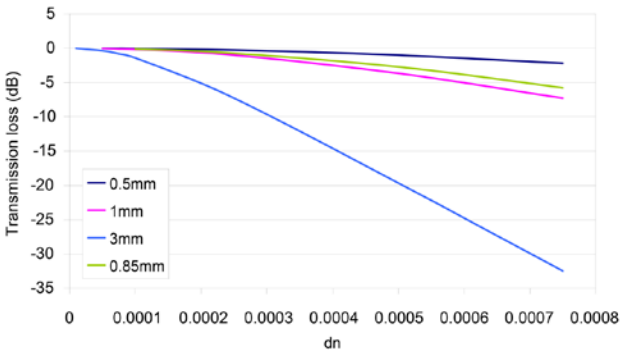


***Figure 9.*** *Variation of transmission loss vs. dn for various grating lengths*

**Conclusion**

The Coherent Azure is an all solid-state laser designed for FBG writing, providing equal or superior output properties as a frequency-doubled ion laser, but with none of the practical limitations in terms of size, stability, power consumption and overall cost of ownership. The data presented here clearly demonstrate that the Azure can produce excellent quality FBGs in a variety of fiber types, including SMF-28: often producing superior results to those created by a frequency-doubled ion laser at 244 nm. As expected, hydrogen-loaded fibers produce superior results because of Azure's 266 nm wavelength, but several doped fibers produce good results even without hydrogen loading.

**References**


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