

Interferometer design for writing Bragg gratings in optical fibers

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ABSTRACT

Bragg Gratings are waveguides, typically single-mode optical fibers, into which a periodic refractive index modulation has been imprinted by a patterned UV exposure. Fiber Bragg Gratings separate telecom frequency bands or compensate for optical dispersion in long-haul fiber networks, and also serve as strain sensors for civil engineering or geophysical studies and oil, gas or mining exploitation. A Bragg Grating writer is an interferometer for generating the UV exposure pattern. It is one of the unusual cases where an interferometer is a production tool, rather than a metrology instrument. In this paper, we review the most common Bragg Grating writing geometry and propose an opto-mechanical structure having minimal adjustment and very high mechanical stability.

Keywords: Bragg gratings, fiber optics, interferometry

INTRODUCTION

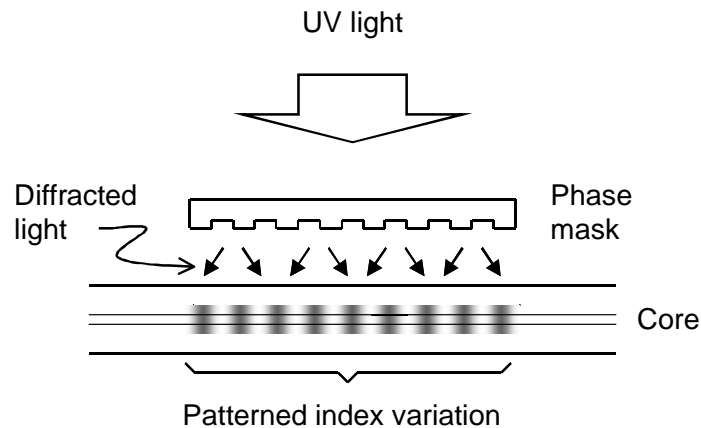


Figure 1: Simple geometry for writing Bragg gratings in a photo-sensitive optical fiber.

Fiber Bragg gratings and similar guided-wave optical filters are phase gratings for which the refractive index of the optical fiber is modulated periodically along the direction of light propagation. The fiber material, typically fused silica,

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is doped in this propagation region (the core in the case of optical fibers) so that it becomes photosensitive. The interference of two mutually coherent, high-intensity UV beams in the doped region induces the refractive index modulation during manufacture. The projected pattern is thus typically a set of parallel fringes having a sinusoidal intensity profile.

In its simplest form a Bragg grating writer consists of a UV laser and a phase mask or diffraction grating placed in contact with the fiber. As shown in Figure 1, the phase mask generates diffracted orders that are created by and interfere in an overlap volume covering the fiber core.

A more versatile apparatus combines a phase mask with steering mirrors to direct the two beams at a well-defined yet adjustable angle of incidence at a given location on the fiber.^{1,2} The flexibility gained by the control of the angle of incidence allows writing gratings over the whole telecom wavelength bands with a single phase mask. Figure 2 illustrates one of the more common geometries following this principle. The UV laser beam passes through the phase mask, generating two divergent beams which are redirected by grazing mirrors to an overlap region in which a periodic exposure pattern is generated by optical interference. A scanning stage displaces the exposure pattern progressively across the fiber to imprint a regular pattern of index variations typically several mm in length during an exposure period often extending to several minutes. A dither stage under computer control modulates or appodizes the effective contrast of the exposure pattern as a function of position along the fiber, in order to tailor the spectral response curve of the resulting Bragg grating.³

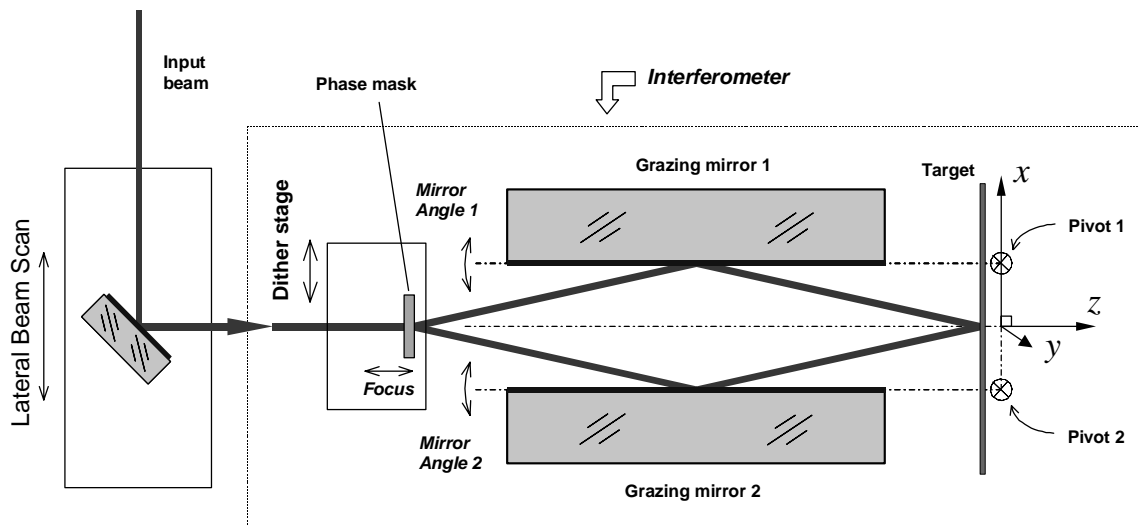


Figure 2: Schematic of the relative positions of the four interferometer components and the coordinate system used in defining dimensions and tolerances.

Many gratings today are fabricated using a writing apparatus comprised of complex staging with multiple adjustments, many of which are redundant, even if this is not always apparent. The multiplicity of adjustments complicates automation of the write process and makes the results unpredictable, often dependent upon the skill and patience of the operator. In this paper, we analyze the tolerance requirements for the Figure 2 geometry and propose an opto-mechanical structure⁴ ideally suited to the task of deterministic manufacture of Bragg gratings.

REQUIREMENTS

The most critical opto-mechanical structure is the interferometer comprising the following four optical components: (1) Phase mask, (2) First grazing mirror, (3) Second grazing mirror, (4) target fiber. Figure 2 shows these key components and defines an x,y,z coordinate system for the BGW with the y axis coming out of the page. The orientation and positions of the components are critical, particularly the stability of these components. Exposure of the target to make a grating structure takes approximately 300 seconds, during which time, the components should remain stable relative to each other to within a few nm.

Analysis of this geometry reveals four fundamental fine-tolerance requirements, summarized in Table 1. There are two blaze angles, horizontal and vertical. For focus, overlap and height, we add an additional requirement that the tolerance be maintained during the lateral scanning of the UV beam. Therefore, there are eight top-level alignment requirements for the BGW. There is one procedural adjustment to tune the interferometer: The Bragg Wavelength, meaning the exact angle between the interfering beams, controlled e.g. by the relative angle $\Delta\theta_y$ of the grazing mirrors. We should be able to make this adjustment at any time without requiring a realignment of the system. Table 2 summarizes this adjustment.

An additional practical requirement is to allow for easy replacement of the mirrors, which degrade rapidly with time because of the intense UV laser beam.

Table 1: Top-level alignment requirements

Alignment	Tolerance	Meaning
Blaze angle	± 0.05 deg	<i>Horizontal:</i> orthogonality of the bisector of the interfering beams with respect to the target. <i>Vertical:</i> parallelism of the plane of incidence to the axis of the target.
Focus	± 10 μm	z location of the interfering beams in the horizontal or x,z plane.
Height	± 10 μm	location of the interfering beams at best focus in the vertical or y direction, which ideally is exactly the same as the height of the target.
Overlap	± 10 μm	relative locations or beam shear of the interfering beams in the vertical or y direction

Table 2: BGW interferometer adjustments that will be made frequently

Adjustment	Resolution	1 st -order contributor
Bragg wavelength	0.0002 deg	Angle of intersection of the interfering beams

DESIGN CONCEPT

The goal of the opto-mechanical design exercise is to allow for all critical interferometer alignments with a high degree of stability while allowing for a tunable Bragg wavelength between exposures, changes in alignment resulting from replacing the target fiber with a fresh sample, and the occasional replacement of the mirrors. Study of the design

requirements leads us to the conclusion that there need only be three independent motorized adjustments under computer control and using a CCD camera as a feedback for the alignment. These adjustments are:

- Phase mask *focus*, meaning the position of the phase mask along the z axis;
- The first angle θ_{y1} of mirror 1 about pivot 1 aligned with the y axis
- The second angle θ_{y2} of mirror 2 about pivot 2 also aligned with the y axis

The grazing mirror adjustment angles θ_{y1} and θ_{y2} serve two purposes. The difference angle

$$\Delta\theta_y = \theta_{y1} - \theta_{y2}$$

control the convergence angle of the beams reflected from the grazing mirrors. This has the effect of controlling the *Bragg wavelength* of the grating imprinted in the target fiber. The average angle

$$\overline{\theta}_y = (\theta_{y1} + \theta_{y2})/2$$

controls the apparent optical reflection angle between the phase mask and the target, and is equivalent to adjusting either the target or the phase mask angle about the y axis to bring these two components into optical alignment. This alignment is important for maintaining proper focus over the entire length of the target. The remaining positions and angles of the components can initially be aligned “at the factory”, so to speak, meaning that these alignments are very infrequent. Additional computer control of the input laser beam angle and height is assumed available via motorized mirror mounts external to the interferometer.

Figure 3 illustrates one design embodiment that achieves the desired adjustable motions while kinematically constraining the remaining angles and positions. Adjustable and lockable balls support bar-shaped grazing mirrors. The mirrors are constrained laterally (e.g. in x and z) by locating pins or similar features (see Figure 4). A spring mechanism holds the mirrors against these pins. The kinematic mounting of the mirrors greatly simplifies replacement of the mirrors for maintenance and recoating, a procedure that can be frequent in some cases because of the intensity and UV wavelength of some illuminating sources used in the manufacture of Bragg gratings.

The base structure comprises two wings that allow for controlled θ_y motion of the mirrors about flexure points shown in Figure 4. The flexures accommodate e.g. a ± 5 mrad range of motion driven by the motorized actuators. The flexures are designed to achieve high stiffness in the x direction perpendicular to the mirror faces for < 5 nm stability during the 300-sec exposure. High stiffness in angular rotations θ_z maintains vertical parallelism of the mirrors indefinitely to a 0.05 mrad tolerance. Of particular importance is the relative parallelism for z -axis rotations θ_z . The mirrors themselves can be manufactured with 0.01 mrad orthogonality tolerances between surfaces, so that when the lower surfaces are parallel, the reflecting surfaces, which face each other, are nominally parallel to the y axis and are vertically parallel to each other to better than 0.1 mrad. This net tolerance includes all sources of misalignment and uncertainty resulting from removal and replacement of the mirrors. The proposed design maintains this angle tolerance without realignment indefinitely.

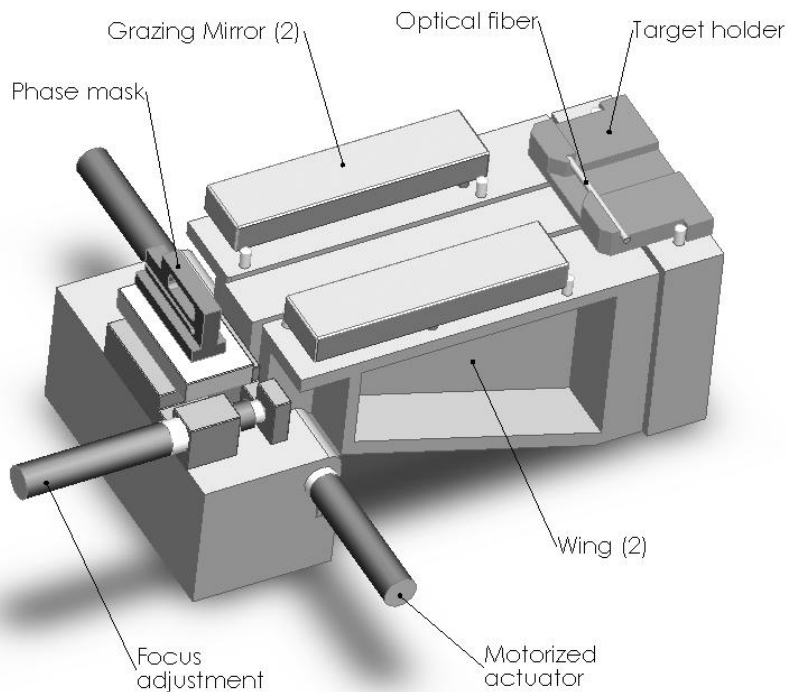


Figure 3: Solid model of the BGW design concept, showing main components.

The target fiber holder likewise rests on adjustable ball supports. The target holder itself is designed so that after locating to the balls, the target is properly located in position and angle to repeatability tolerances of 0.005 mm and 0.05 mrad, respectively. There are two possible use modes, a first in which the target alone is removed and replaced between exposures while the holder remains fixed, and a second in which the entire target holder including the target is removed and replaced for every exposure. The design accommodates both eventualities, and in either case, an additional clamping mechanism may be included for both the target and the target holder, using e.g. magnets, springs or other compliant mechanism. The top and rear of the target are left unobstructed to light paths for alignment purposes. An important feature of the design is that there are several target holders having a range of target heights in the y direction. This accommodates raising and lowering the working height of the light beam between measurements so as to more evenly distribute the damaging effects on the mirrors and on the phase mask of intense UV illuminating sources.

The phase mask is most often a 12.5 X 25.4 mm rectangle. A phase mask holder allows for an adjustment θ_z using a fine screw and a flexure. This is a critical adjustment but it need only be made when a phase mask has been replaced. The x and y positions are not critical. The z of focus motion is controlled by a motorized stage, and it is important that the stage not introduce angular motions >0.02 mrad along its full range. The θ_y angle about the vertical axis y is kinematic for relocation of the phase mask and for removal and replacement of the phase mask holder to a total tolerance of 0.5 mrad. The initial setup of this angle to the nominal value of parallel to the x axis requires some one-time adjustability, perhaps of the focus stage orientation. The design presumes a set up of the tip angle θ_x to within 1 mrad using mechanical tolerances only, given that the focus stage and phase mask modulator have precision parallel surfaces.

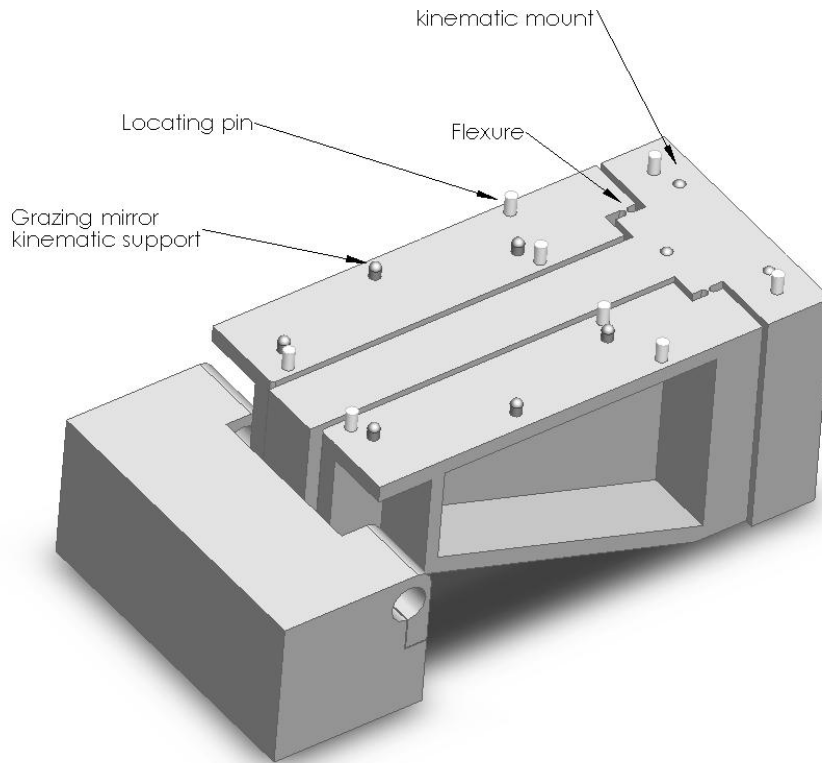


Figure 4: Solid model of BGW base structure, showing kinematic mounting scheme.

ALIGNMENT

Equally important to the opto-mechanical design is the alignment procedure. Because the writing process relies on the absorption of UV radiation in the doped fiber core, the complex mechanisms that take place in the material result in fluorescence at visible wavelengths as well as scattering of the UV radiation and localized heating. A key aspect of the proposed interferometer alignment scheme is the realization that the location and amount of fluorescent light generated by the doped fiber provides information about the alignment state of the system.

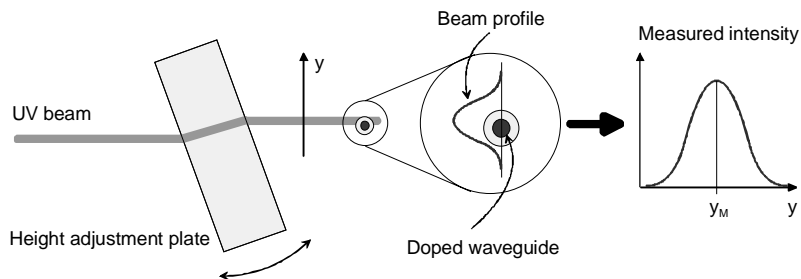


Figure 5: Vertical beam sweep to find the fiber core vertical position.

Figure 5 through Figure 8 illustrate three different uses of the fluorescence phenomenon for alignment. Figure 5 shows one possible means of sweeping a UV beam to determine the vertical position of the fiber core. A parallel plate is tilted by various amounts, causing a displacement of the illumination beam. Maximum fluorescence is observed when the beam is centered on the core of the fiber. The fluorescence measurement can be performed using for example a photodiode or a camera. The profile of measured intensity as a function of sweep position is analyzed to find the position of best overlap. Figure 6 illustrates focus detection by sweeping or stepping through focal positions and observing the separation of the fluorescent zones generated by the beams as a function of focus position. Figure 7 is an experimental image of these zones captured with a CCD camera. Figure 8 illustrates a determination of beam overlap by alternately blocking first one then the other beam and observing how the exposure area shifts. These basic alignment techniques combined with displacement of the scanning mirror shown in Figure 1 to different target locations are the key elements in the alignment cycle which can rapidly verify critical alignments of the complete system. Experimental verification indicates that the alignment technique safely satisfies the tolerance requirements of Table 1.

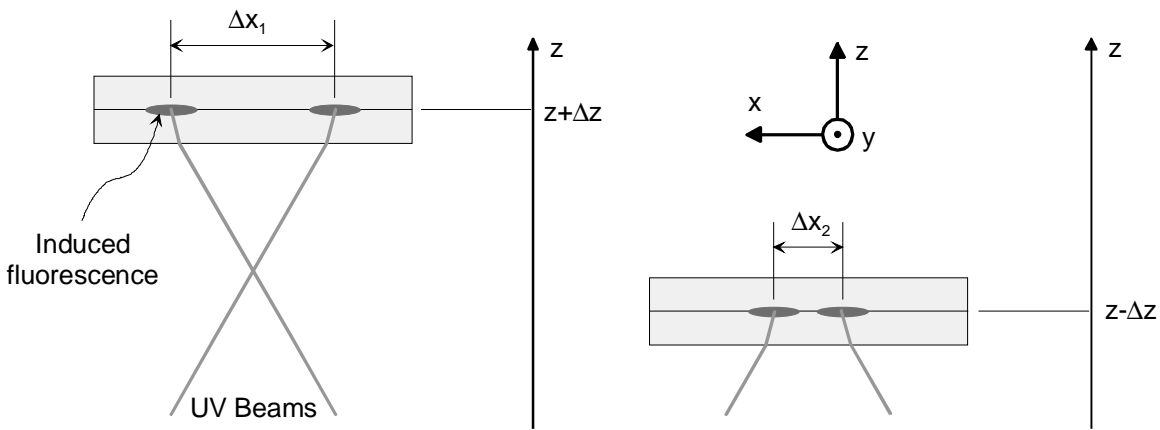


Figure 6: Determination of best-focus by displacement of the target fiber.



Figure 7: Fluorescence image recorded for a 20- μm fiber core, in the case of a large beam shear. The difference in intensity is due to a vertical misalignment of one beam.

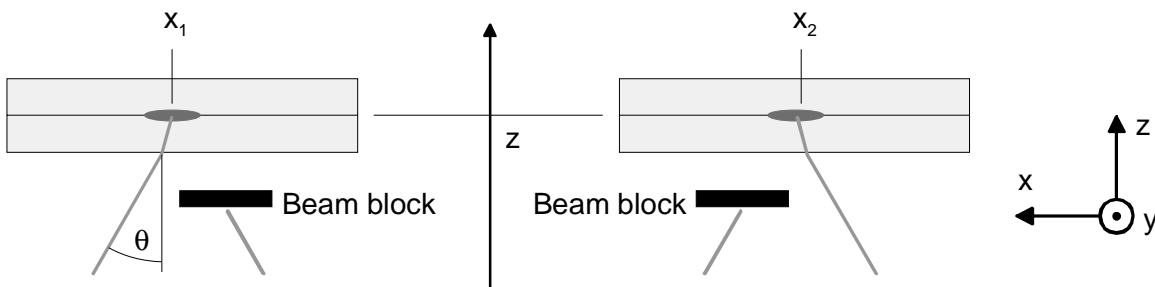


Figure 8: Beam shear measurement based on separate exposure of the two UV beams.

CONCLUSION

The key conclusions of the present design study are as follows: By means of a robust design, the number of independent, frequent adjustments of a Bragg grating interferometer can be reduced to three motorized actuators under computer control. The feedback mechanism for alignment may be image analysis of the fluorescence in the target fiber, coupled with controlled redirection of the UV exposure beams (e.g. sweeps across the fiber or changes in focus). Kinematic mounting facilitates easy replacement of the bar-shaped grazing mirrors.

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 - 4 The interferometer design and alignment technique are the subjects of US and Foreign patents pending.