

FBG Based Distributed Lighting for Sensing Applications

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Abstract: An efficient distributed light source has been developed for line scan sensing. The source is based on diffracting light from a highly blazed grating written in the core of a single mode fiber.

1. Introduction

A distributed light source has been developed for illuminating rectangular regions with uniform power density. Light from a fiber coupled source is distributed by a long highly blazed fiber grating and collimated by a cylindrical element. An irradiance of 1 mW/cm² has been generated at 1550 nm. Line scan cameras sense the presence of moving objects by reading one row of pixels at uniform temporal increments. Many objects are inspected in this manner - including foodstuffs, produce, paper, currency, and recyclables. An efficient lighting arrangement should distribute significant power density over a rectangular region that is conjugate with the row of pixels in the line scan camera. This requires a highly directional, distributed source. Line scan cameras with high spatial resolution require object plane power densities approaching 1 mW/cm² such that each pixel can collect useful signals in acceptable integration times [1]. In addition, the power density must be uniform within a few percent inside the entire rectangle (often 5 to 25 mm high by 1 m long). The lighting distribution optics must function over a wide spectral range and be compatible with practical light generation devices.

Existing linear lighting technology includes cylindrical tungsten halogen lamps, arrays of light emitting diodes (LEDs), laser line generators, arrays of fiber tips, patterned lightguides, and side emitting fibers [2]. These approaches do not combine sufficiently intense uniform power density in a directional beam without thermal loading. The following sections describe the design, fabrication, and evaluation of a new light source that meets these requirements.

2. Design and Fabrication

Figure 1 depicts the new distributed light source, which integrates fiber Bragg gratings and a cylindrical optical element (PLI patent pending). The key aspect is a 45° blazed diffraction grating written in the core of an optical fiber [3]. Incident guided light is diffracted from the core at nearly 90 degrees to the fiber axis. The resulting beam is collimated by a cylindrical surface positioned three radii from the fiber.

Gratings were written in single mode deuterium loaded matched clad fiber with a 9.7 micron mode field diameter. The writing system used an excimer laser at 248 nm and a phase mask in the +1/-1 configuration. The laser beam was scanned across an aperture placed near the mask such that a uniform dose was received by all points within the aperture. The diffraction equation relates the outcoupling angle (ξ) to relevant grating parameters as follows:

$$(n_{\text{eff}}d/\cos\theta) (1 + \cos\xi) = \lambda ,$$

where n_{eff} (1.445) is the effective index in the core, d (0.8835 microns) is half of the phase mask pitch, θ (33.3 degrees) is the phase mask tilt angle relative to the fiber axis, and λ is the center wavelength. Because of cylindrical lensing in the fiber, the resulting internal blaze angle (θ_{Internal}) is roughly 45 degrees: $\tan\theta_{\text{Internal}} = n_{\text{UV}} \tan\theta$,

where n_{UV} is the refractive index of silica at 248nm. These parameters generate outcoupling at ξ near 90 degrees for a center wavelength of 1550 nm. The 45 degree blaze ensures high outcoupling efficiency at 90 degrees to the fiber. Similar high blaze fiber gratings have been used in all-fiber polarimeters [4] and polarizers [5]. After grating fabrication, fibers are bonded to a cylindrical optical element with an optical adhesive.

The diffraction equation predicts how ξ varies with λ , and the volume current method (VCM) can be used to model the azimuthal distribution along the angle φ [6]. As shown in figure 1, the diffraction angle ξ lies in the XZ plane while the azimuthal angle φ lies in the YZ plane (where X is the fiber axis and Z is the optical axis of the outcoupled beam). The angle ξ varies by about ± 5 degrees over $\lambda = 1550 \pm 150$ nm. This small variation in ξ is due to the low dispersion of gratings at these high blaze angles. VCM models have shown that one strong azimuthal lobe exists over a bandwidth of about 300 nm [7]. After the bonding step, a fiber pigtailed light source is connected to the fiber. Useful sources include diode lasers, fiber lasers, amplified spontaneous emission sources, and super-continuum sources. In all cases, single mode fiber is required for efficient grating coupling. The state-of-polarization (SOP) of polarized sources must be aligned to the blaze angle.

For specified power density (P) and beam height (H - along the Y axis) in the object plane, fiber coupled device power (I) and grating strength (S) are related by the following inverse relation:

$$P(\text{mW}/\text{cm}^2) * H(\text{cm}) = I(\text{mW}) * S(\text{cm}^{-1}).$$

If S is a constant, P will vary as $\exp(-SX)$ along the length of the grating. If S is varied along the fiber axis, P can remain constant along the X axis.

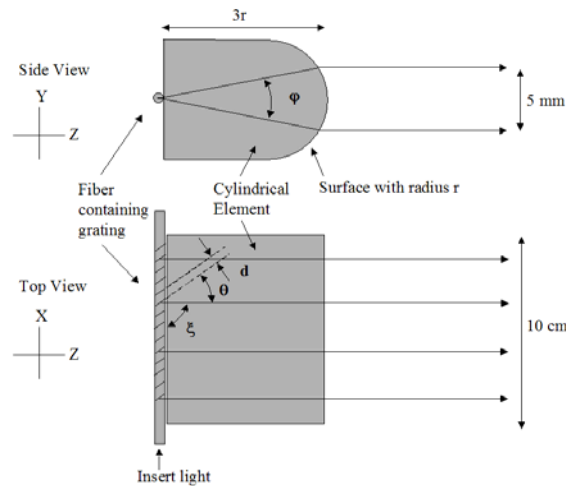


Figure 1. Geometry of the distributed light source [7]

3. Results

This paper presents the spatial and spectral characteristics of long uniform highly blazed gratings – establishing the viability of the design. Figure 2 shows the spatial uniformity of 5 cm long gratings of two strengths – 0.001/cm and 0.0033/cm. The images in figure 2 were taken with an InGaAs 2D camera focused on a plane 30 mm from the fiber axis without the cylindrical optical element. The plots correspond to pixels along the middle of the two illuminated rectangles. The vertical axis was scaled to predict power density expected with a 400 mW laser (3 mW at 1550 nm was used to generate this data). Longer gratings can be fabricated if twist is minimized with appropriate fixtures. Multiple gratings can be stitched together to circumvent phase mask length limitations. Spectral bandwidth was evaluated by measuring power in the central region of the illuminated rectangle while the wavelength was swept from 1510 to 1640 nm (the spectral range of an available tunable laser). A polarization controller was used to align the laser's SOP to the blaze angle. Figure 3 shows that the S-polarization power is nearly constant over 130 nm. Further, images of the stripe did not change in appearance as the wavelengths were scanned. In addition, the polarization controller was used to flip from the S to P polarization states. Figure 3 also shows a scan taken with P polarization. The delta between the S and P curves exhibits the expected high PDL of these high blaze gratings.

Images of the full rectangle taken with P polarization reveal little or no brightness – this observation indicates that grating induced birefringence is not causing an observable evolution of the SOP along the length of the gratings. Low fiber birefringence, high writing concentricity, and post-writing annealing enables the absence of this evolution and encourages the fabrication of longer gratings.

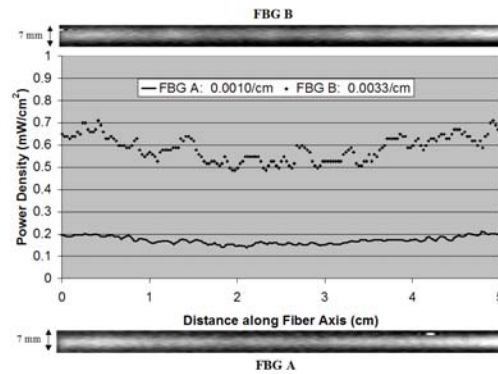


Figure 2. Measured spatial power distributions for two FBG light sources (images of each source above and below the plot)

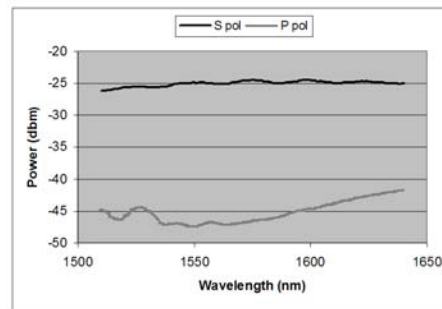


Figure 3. Maximum and minimum measured spectral power distributions.

4. Conclusions

A novel fiber grating based distributed light source for line scan sensing has been designed, fabricated, and tested. The spatial uniformity ($\sim 10\%$) and spectral bandwidth (300 nm – pending available wavelengths from fiber coupled devices) encourages the development of longer gratings. We expect this approach will provide key improvements in the length, efficiency, brightness, thermal management, and lifetime of lighting solutions for line scan sensing applications spanning numerous economic sectors.

5. References

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