A fiber grating based distributed light source

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ABSTRACT

Line scan cameras are used for rapidly monitoring a moving web or sheet of material. Lighting for line scan inspection should illuminate a long narrow rectangle, which is imaged onto the linear array of pixels in a line scan camera. This distributed light source should provide a uniform power density at the desired wavelengths. Tungsten halogen lamps and LED arrays can meet many of these objectives, but not in a highly directional beam with minimal thermal issues. We have developed a new distributed light source that is based on diffracting light from a highly blazed grating written in the core of a single mode fiber. The grating is blazed such that out-coupling is 90 degrees to the fiber axis. The fiber is bonded to a cylindrical optic that collimates the azimuthal power distribution. Connecting a single laser diode to the fiber can generate 1 milliwatt per square centimeter over a 10 cm by 0.5 cm rectangular region. Longer gratings and/or multiple segments can be connected to illuminate longer regions. The distributed power density, spatial uniformity, degree of collimation, and spectral bandwidth of these illuminated rectangles are reported. This highly directional distributed source will enhance the utility of line scan cameras in multiple applications.

Keywords: light source, fiber gratings, optical inspection

1. INTRODUCTION

Line scan cameras generate 2D images by reading one row of pixels for each position of a moving object. 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. As depicted in figure 1, this requires a highly directional, distributed source. Further, line scan cameras with high spatial resolution require object plane power densities of about 1 mW/cm^2 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). An efficient lighting arrangement should also avoid illuminating area outside the rectangle. The angular distribution of the emitted light must allow the power density requirements to be met with working distances (often several cm to about 0.5 m) that are compatible with a given inspection system. Further, the wavelength dependence and efficiency of the lighting distribution optics must be compatible with practical light generation devices.

Existing linear lighting technology includes cylindrical tungsten halogen lamps, arrays of light emitting diodes (LEDs), arrays of fiber tips, patterned lightguides, and side emitting fibers. Tungsten halogen lamps are low cost, but suffer from low intensity, poor directionality, poor efficiency, and thermal loading issues. LED arrays are widely available, but a large number of sources are required to create a uniform power density. One source coupled to a large number of distributed fiber tips[2] can also create a uniform power density. Patterned lightguides with surface relief on one sidewall scatter light out of the guide toward the illuminated target. This basic approach has been addressed in several ways[3]: holographic scatter centers written on the back sidewall, prismatic scatter centers placed on the emitting surface, facets

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placed on the back sidewall, and facets placed on a 2D surface for LCD illumination. These scatter based methods can create uniform illumination, but are subject to tradeoffs between efficiency and uniformity. Side-emitting fibers emit light in many directions by using either "leaky" modes or by placing randomly positioned scatter centers in the core.[4]

None of these approaches combines sufficiently intense uniform power density in a directional beam without thermal loading. We have developed a fiber grating based distributed light source that meets these requirements. The following sections describe the design, fabrication, and evaluation of this new light source.

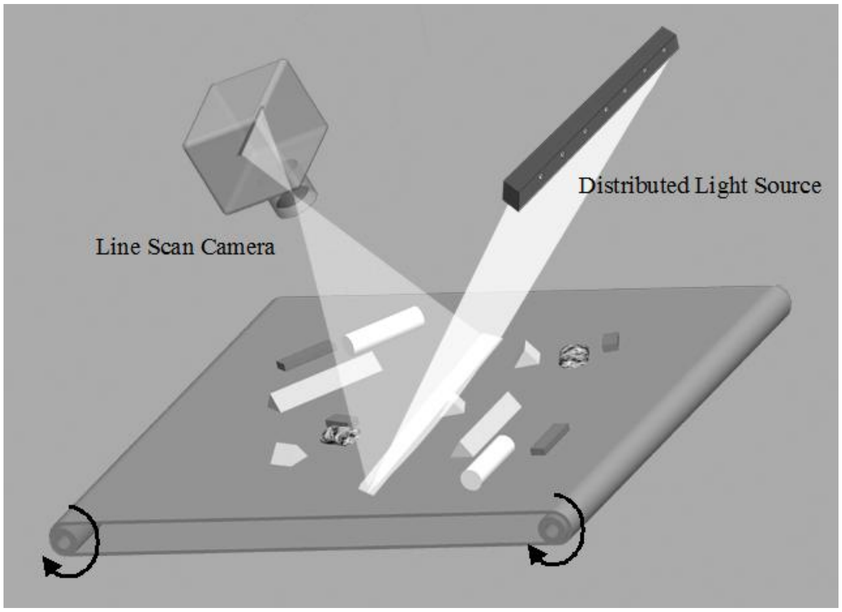

Figure 1 – Distributed Light Source with Line Scan Camera

2. DESIGN AND FABRICATION

Figure 2 depicts the new distributed light source, which integrates fiber Bragg gratings and a cylindrical optical element. The key aspect is a blazed diffraction grating written in the core of an optical fiber. 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 phase mask was oriented approximately 33.3 degrees relative to the fiber during exposure. The laser beam was shaped by a one centimeter aperture and then scanned across a two inch aperture placed near the mask such that a uniform dose was received by all points within the aperture. The scan started before and ended after the two inch aperture. The fiber orientation was then keyed and the fiber shifted two inches relative to the aperture. Keying is necessary to insure light from each two inch section is ejected in the same plane. A second laser scan across the two inch aperture exposed an adjacent two inch long fiber Bragg grating. The gap between the gratings is less than 1 mm. The diffraction equation relates the outcoupling angle (ξ) to relevant grating parameters as follows:

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

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 ($\theta_{Internal}$) is roughly 45 degrees:

$$\tan\theta_{Internal} = n_{UV} \tan\theta$$

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[5].

After grating fabrication, the fiber was bonded to a 12 inch long cylindrical optical element with an optical adhesive. The optical element was purchased from a vendor who used extruded silica tubing to fabricate the shape (r = 6 mm) shown in figure 2.

The diffraction equation predicts how ξ varies with λ, and the volume current method[6] (VCM) can be used to model the azimuthal distribution along the angle φ. As shown in figure 2, 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. Figure 3 shows the VCM derived azimuthal power distribution at both 1550 nm and 1400 nm (the curve at 1700 nm is similar to the curve at 1400 nm). One can see that the sidelobes at 150 nm from the center wavelength are starting to gain strength at the expense of the central lobe. At wavelengths yet further from 1550 nm, the central lobe breaks up into multiple smaller lobes. This effectively limits the bandwidth of one grating to about 300 nm.

A raytrace was performed to translate the φ distribution inside the optical element to the spatial distribution along the Y axis outside the optical element. With the fiber located three radii from the curved surface, we expect paraxial rays to be collimated. Figure 4 shows that the central lobe translates into a beam with FWHM = 5 mm (in the Y direction). The lower sidelobes are affected by spherical aberration and are not expected to collimate. Further, when $\xi \neq 90$ degrees, refraction at the exit surface of the optical element leads to a moderate angular broadening in the XZ plane.

After the bonding step, a fiber pigtailed light source was connected to the fiber at the bottom of figure 2. Various sources can be used - including 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. Using sources that generate light within a single mode fiber (for example fiber lasers) avoids coupling loss encountered during the packaging of diode sources. A Princeton Lightwave pigtailed DFB laser that emits 250 milliwatts at 1550 nm was used in this evaluation.

For specified power density (P) and beam height (Y_o) in the object plane, source power (I) and grating strength (S) are related by the following inverse relation:

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

If S is a constant, P will vary as exp(-SX) along the length of the grating. This case is plotted in figure 5 for S = 0.005 cm^{-1}. This exponential falloff can be tolerated in a 10 cm long distributed source. Longer sources can be made more uniform by using two counterpropagating constant strength gratings (also shown in figure 5). A more elegant solution is to vary S such that P remains constant along the X axis (the topic of a future paper).

The distributed light source has been mounted in a rigid package, which can be configured for various lengths. Extra gratings stitched together in one fiber, or placed end-to-end in separate fibers, can be used to increase the length of the illuminated rectangle. One dimensional diffusers can be used to improve spatial uniformity by blurring along the X direction to avoid the effects of phase mask defects and stitch points.

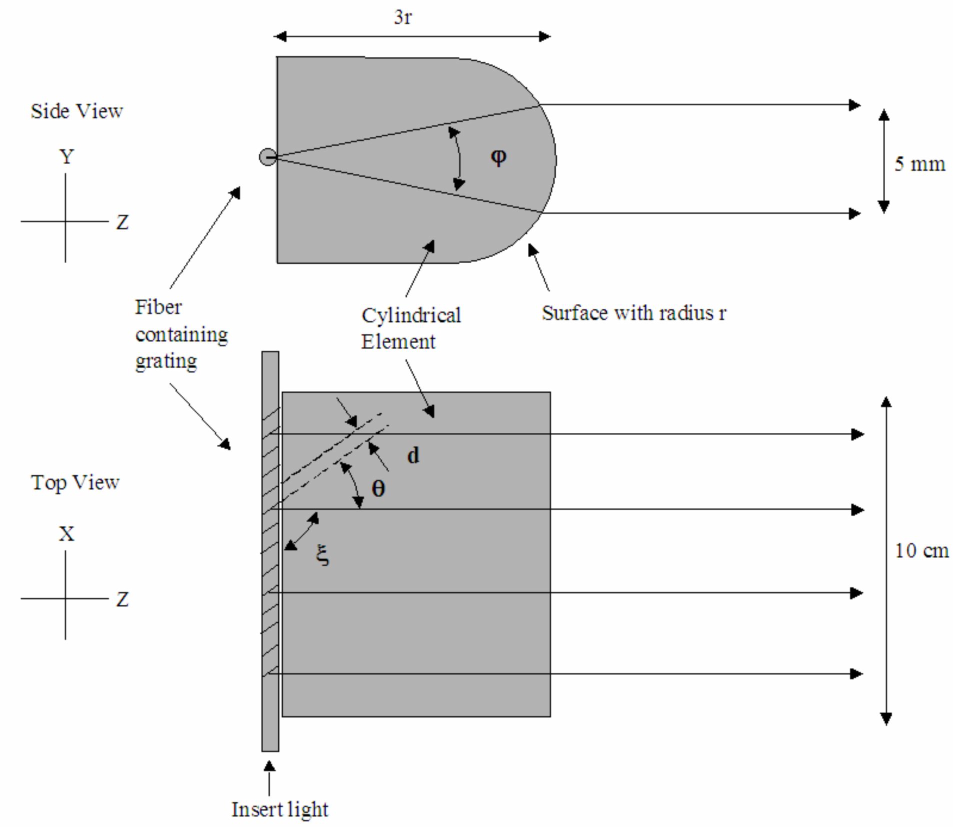

Figure 2 – Geometry of Distributed Light Source

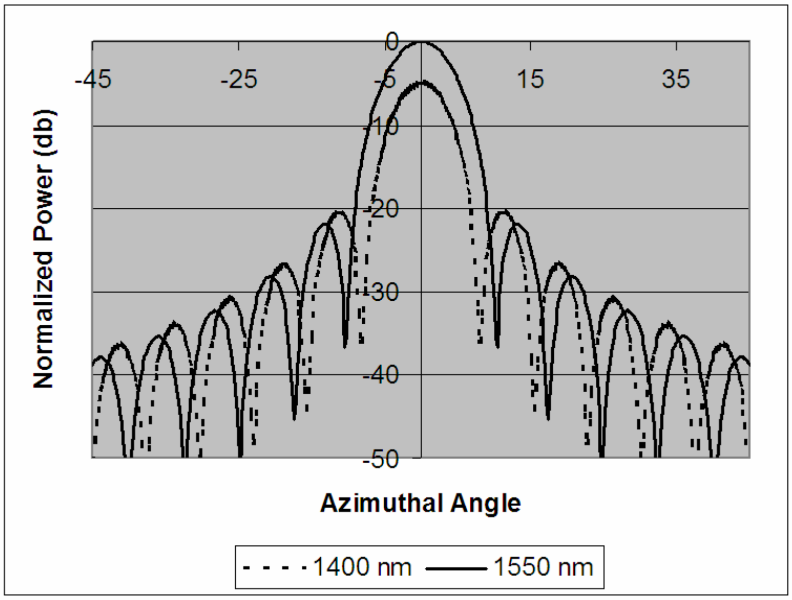

Figure 3 – Modeled Azimuthal Power Distribution inside Lens

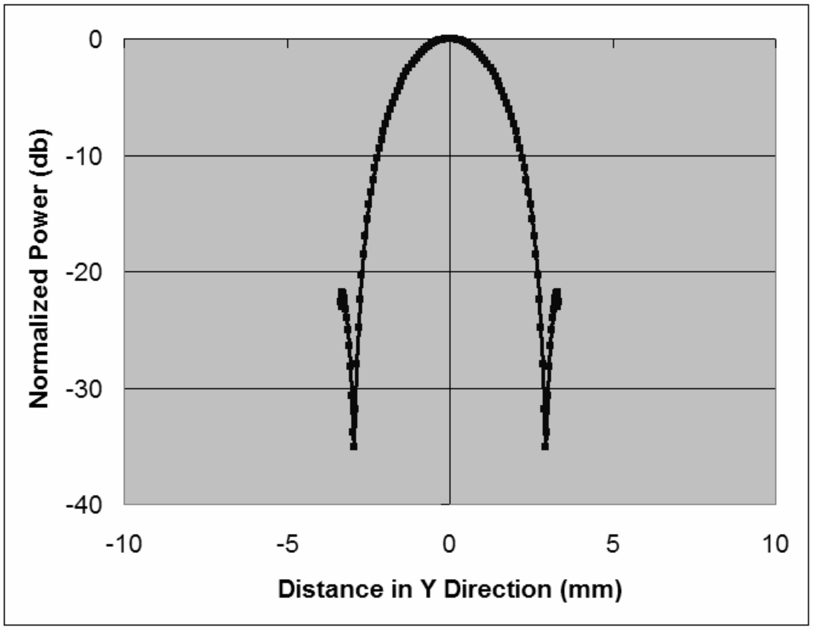

Figure 4 – Modeled Power Distribution along Y Axis outside Lens

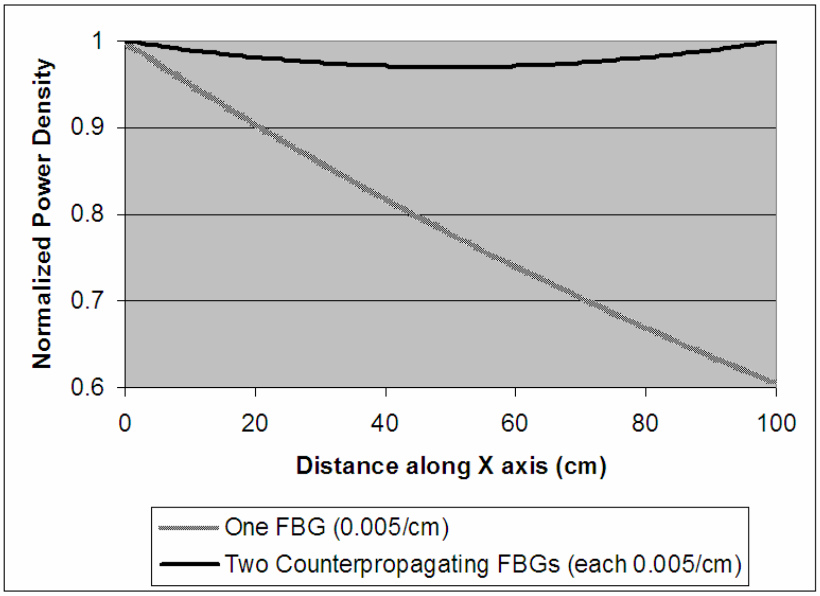

Figure 5 – Depletion Models

3. RESULTS

The spatial uniformity of a prototype of the distributed light source is shown in figure 6. The prototype was fabricated with one fiber containing two stitched gratings with a constant strength of 0.005/cm. The image was taken with an InGaAs 2D camera and digitized into 256 grey levels. The profile was taken across the middle of the image. Fluctuations in the profile are due to phase mask defects. A gradual falloff from right to left is consistent with the single fiber curve in figure 5 for a 10 cm length.

The power density at the right side of figure 6 was adjusted from about 0.25 to 1 mW/cm^2 by changing the power of the DFB laser diode from 25 to 100 mW. These power densities are compatible with the operation of high pixel density line scan cameras. In the current configuration, the prototype is only illuminating the rectangle with about 5% of the incident optical power. Longer designs would use more of the incident light. Even at the low efficiency of the current prototype, the source remains at room temperature and all thermal loading issues are avoided.

The degree of collimation was evaluated by measuring the height of the illuminated rectangle in the near field (5 mm), at a working distance of 3 inches (12 mm), and at a working distance of 6 inches (25 mm). The observed beam expansion could have been minimized by placing the fiber slightly further from the curved surface (at the "circle of least confusion" to compromise between paraxial and non-paraxial rays).

The spectral bandwidth of the prototype 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. Outcoupling is nearly constant over the 130 nm (consistent with the 300 nm bandwidth prediction from figure 3). Further, images of the stripe did not change in appearance as the wavelength was scanned. Finally, ray angles in the XZ plane outside the optical element varied by 7.7 ± 1 degrees during the spectral sweep (consistent with expected values - 4.9 degrees inside the optic and 7.1 degrees outside the optic).

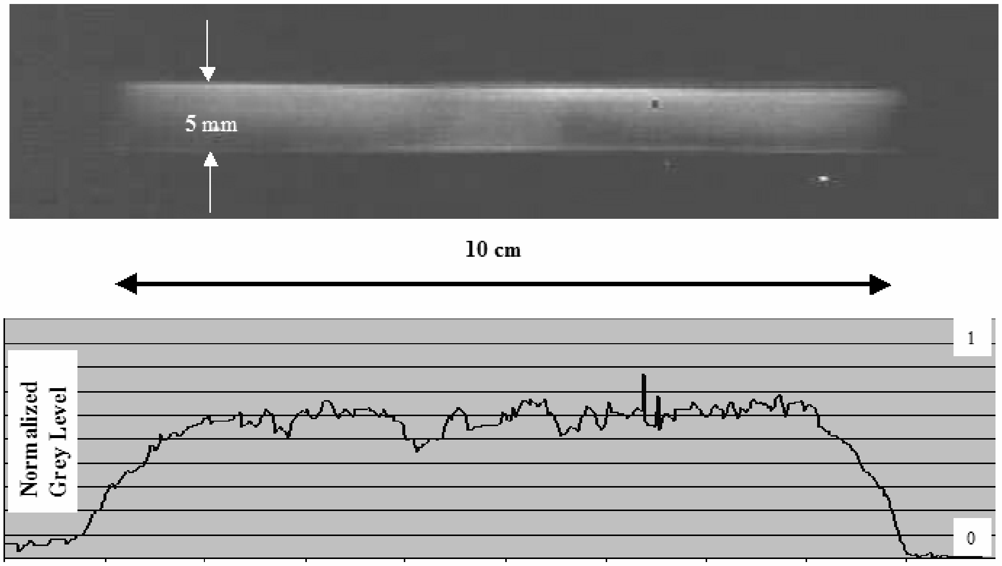

Figure 6 – Measured Power Distribution

4. CONCLUSIONS

A novel fiber grating based distributed light source has been designed, fabricated, and tested. The source illuminates a rectangular region (10 cm long by 5-25 mm high) with a power density of 1 milliwatt per square centimeter. The power density is uniform to within ± 10%. A flat spectral bandwidth was measured over 130 nm and predicted over 300 nm.

Longer lengths (approaching 1 meter) are possible by writing longer gratings and/or by stitching multiple gratings together in one fiber. Multiple fibers can be bonded to the same cylindrical element to cover an extensive bandwidth – contingent on laser availability at required wavelengths.

Multiple inspection applications will benefit from coupling this new distributed light source with high pixel density line scan cameras - including Princeton Lightwave's new dual band camera.[1]

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