Dragonfly directional sensor

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Abstract. This paper discusses the concept and hardware development of an all fiber-based, solid state, coherent array directional sensor that can locate and track bright objects against a darker background. This sensor is not an imager. It relies on the inherent structure of the global fiber distribution. Methods for characterizing and calibrating hardware embodiments are also presented. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.52.2.024403]

1 Introduction

Dragonfly is a fiber-optic based directional sensor being developed under U.S. Army auspices. This sensor is being developed in order to locate and track one (or multiple) bright objects in terms of azimuth and elevation. The concept[1] is illustrated in Fig. 1.

The Dragonfly optic is not a lens, nor an imager. It is a nonconventional optic consisting of a very large number of optical fibers (core and cladding) in a fused coherent array.[2] Only five, of the multitude, of fibers are illustrated in the drawing. The convex surface looks outward for targets. The flat side is coupled to a focal plane array (FPA) either by a relay optic or by direct attachment as shown in Fig. 1. Each fiber in the array is perpendicular to both the convex and flat surfaces (and each flat fiber face is tangent to both the convex and flat surfaces). Due to the structure, each fiber on the convex side points in a specific azimuth and elevation direction. An annular ring on the flat side corresponds to a certain elevation angle, while any point on that ring corresponds to a specific azimuth angle as shown in Fig. 2.

Each fiber, on the convex side, has a numerical aperture dictated by the refractive indices of the core and cladding. This defines the narrow field of view (NFOV) as indicated in Fig. 1. The full FOV (FFOV) is determined by the total arc across the convex surface along a diameter. This is ± 90 deg as illustrated in Fig. 1.

2 Physical Embodiment of the Concept

A prototype embodiment of the concept is shown in Fig. 3. It was built by Schott North America located in Southbridge, Massachusetts. The FFOV for this prototype is ± 45 deg, and consists of approximately 2.8 million individual optical fibers. In this example, the aperture diameter of the convex surface is 35 mm with a radius of curvature of 19 mm. The flat surface has a 5.2 mm diameter [in order to eventually interface directly to a charge coupled device (CCD) chip]. As you can see, the larger convex surface is connected to

the flat surface via a taper. The taper length, here, is 45 mm. Fiber diameters on the convex surface are significantly compressed on the flat surface. Depending on the taper length, this compression can be a factor between 5X to 7X. (For example, if an individual fiber face on the convex side is 15 μm then, on the flat side, the diameter could be in the range of 2 or 3 μm). On the flat side, this results in six to ten fibers per pixel (depending on pixel size). The taper also affects the NA of a fiber. On the convex surface, this translates to a narrowing of the NFOV. On the flat side, the NA is ≈ 1.

Fibers, in the coherent array, are arranged in blocks of five fibers each as shown by the micrograph (right) in Fig. 4. There are four transmissive fibers and one non-transmissive black fiber. (Drawing on left helps clarify the geometry). Note that the transmissive fibers are not round. The central (round) black fiber helps reduce cross-talk between the transmissive fibers. (It also slightly reduces net transmission).

As already mentioned, the optical fibers must be perpendicular to the convex surface in order to function as a directional sensor. Figure 5 helps to illustrate the reason why.

Now, apply this to the convex surface of Fig. 3 as illustrated in Fig. 6. Here, we show two fibers. Fiber A is perpendicular to the convex surface (and its face is tangent to that surface). The face of Fiber B is also tangent to the convex surface, however, the fiber is not perpendicular to the face. Now, consider a ray running parallel to the fiber wall in each case. For Fiber A, the ray emerges parallel to the surface normal however, for Fiber B, the emerging ray does not follow the surface normal but bends away from the surface normal as per Snell's Law.

As a simple qualitative check to make sure the Dragonfly optic is behaving, we focus a small spot of laser light on the flat side at several locations as illustrated in Fig. 7(a). Next, we observe the departure angle of the light as it leaves the convex surface. If built correctly, the respective angles will
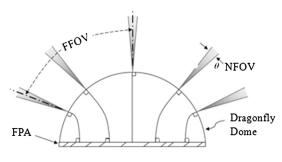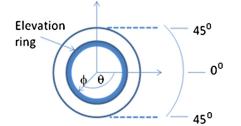
Fig. 1 Dragonfly concept drawing.

Fig. 2 Fibers in a common ring have the same elevation angle φ while each fiber in that ring has a specific azimuth angle θ.
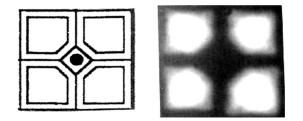

Fig. 3 Dragonfly optic physical embodiment.

Fig. 4 Typical block arrangement of fibers in the coherent array.

Fig. 5 A ray propagating parallel to fiber wall will emerge from fiber face at an angle dictated by Snell's Law.

bright target. The instrument used to measure the NFOV will be discussed in Sec. 5.

3 Spectral Regions of Application Interest

Many munitions exhibit a strong potassium signature in their launch/exhaust plumes. An example is shown in Fig. 8. Note the spectral spike around $\lambda = 770$ nm. The Schott core glass, in the current set of prototypes, can easily transmit that wavelength as shown by the spectral transmittance plot in Fig. 9.

However, the Army's interests extend well into the near infrared (NIR) and mid infrared as well. Fortunately, core glass No. 24 can make deep inroads into the NIR region as shown by the FTIR plot in Fig. 10. Transmission at $\lambda = 2.5 \mu$ is close to 70 percent. At $\lambda = 3 \mu$ transmission drops to 17 percent, and 3 percent at $\lambda = 3.4 \mu$.

4 Dragonfly Sensor Configurations

The Dragonfly optic, basically, looks for bright objects (against a darker background) entering the NFOV of any individual fiber which then reports it to a pixel location on the FPA. The coupling to an FPA can be accomplished either by a relay optic or by direct contact. An example of the former is shown in Fig. 11.

The Dragonfly optic is on the extreme left. A relay lens sits in the middle. Next, comes an interference (spike) filter for 770 nm which sits directly in front of the CCD camera mount. The CCD is on the extreme right. If we could butt the

be leftward for A, centered for B, and rightward for C. The qualitative empirical results are shown in Fig. 7(b).

Note that the illuminated spots on the screen have irradiance structure. Measuring that structure is important for two reasons. The first will help define the NFOV of the Dragonfly sensor. The second reason is tied into calculating the effective aperture of the Dragonfly optic when observing a distant
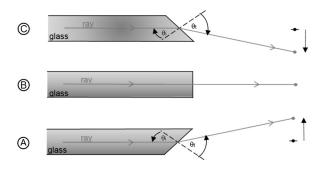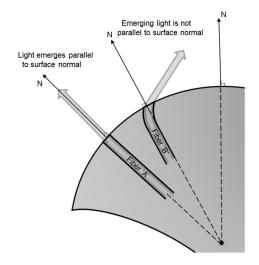

Fig. 6 Optical fibers must be perpendicular to the convex surface in order to function as a directional sensor.
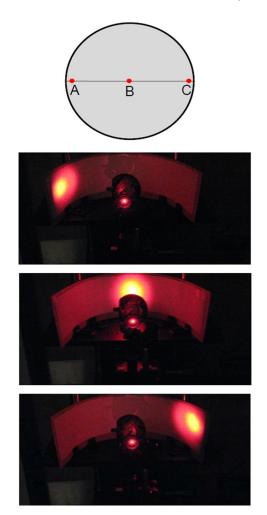
Fig. 7 (a) Focused laser spots on flat side of Dragonfly optic; (b) propagated light emerging from convex surface and illuminating areas on screen in proper sequence A (top), B (middle), C (bottom) [as per Fig. 7(a)].

Dragonfly optic directly up against the CCD chip, the axial length of the sensor could be considerably shortened as illustrated in Fig. 12.

The arrangement, shown in Fig. 12, assumes that any protective window over the CCD chip has been removed. This is because the NA, on the flat side of the Dragonfly, is so high.

Any significant spacing between the two would be detrimental to angular resolution. A future goal, however, is to "glue" a CCD chip directly to the flat side. The main concern is the potential for Moire fringing between the rectilinear grid of the CCD and the grid structure of the fiber array. Regardless of how the connection is made between the Dragonfly optic and the FPA (or CCD), a Dragonfly system lends itself to very small, compact, rugged, and lightweight packaging suitable for a wide range of applications and platforms. Whether by relay or direct contact, the FPA pixels are calibrated in terms of the polar (azimuth and elevation) directions inherent to the Dragonfly optic which allows it to locate and track one, or multiple, bright objects within its FFOV.

5 Characterizing and Calibrating Dragonfly

Schott had the technology to build the Dragonfly prototypes based on its broad experience with coherent fiber arrays in various shapes and forms. However, their array products are traditionally built and used for image transfer not for directional sensing. This was a new and unusual application for a coherent array. One consequence was that neither Schott nor the Army had the in-house capability to test and evaluate such novel devices. Setting up a characterization and calibration lab was a task assigned to the CAO at UA Huntsville. Data collected, and analyzed, at this facility will provide a better understanding of Dragonfly performance issues and will (in partnership with Schott) lead to improved product development. The Dragonfly Lab has six measurement stations. A brief description of each now follows.

5.1 Angular Profile Station

The APS system, shown in Fig. 13, provides data on the shape of the narrow field of view (NFOV) on the target (convex) side as a function of the microscopic light input footprint on the flat side. For sampled footprint locations on the flat side, the angular size and shape of the NFOV is determined. Currently, angular profiles are obtained across two orthogonal diameters. Figure 14 shows a sample data plot. This data provides the angular irradiance structure associated with the qualitative pictures in Fig. 7(b).

The physical scans are always made in azimuth. However, the Dragonfly optic is easily clocked in its mount to acquire APS across any diameter.
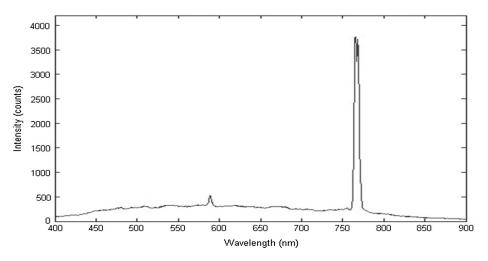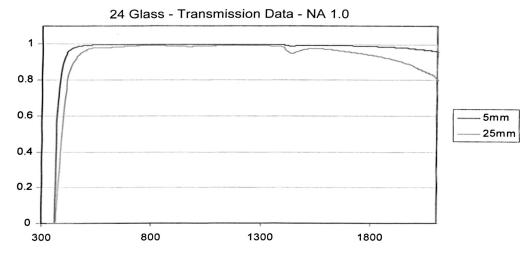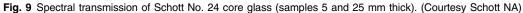

Fig. 8 Example of a munitions potassium spectral signature.

24 Glass - Transmission Data - NA 1.0

Fig. 9 Spectral transmission of Schott No. 24 core glass (samples 5 and 25 mm thick). (Courtesy Schott NA)
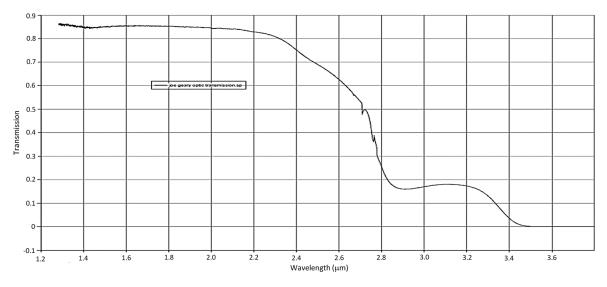

Fig. 10 FTIR plot of a 5 mm thick No. 24 core glass sample.

5.2 Directional Calibration Station

The DCS is used to tie a CCD pixel location to a specific azimuth-elevation direction. The Dragonfly optic is connected to a digital CCD via a short focus relay lens. This Dragonfly system is mounted to dual axis rotation stages as shown in Fig. 15. The rotation axes are orthogonal and coplanar. The vertex, of the Dragonfly convex surface, is made coincident with the point where these axes cross. A collimated white light beam stays centered on the Dragonfly optic as it is rotated. Typically, a single azimuth scan is made across the FFOV as well as a single elevation scan. However, a full raster calibration can be done as per customer requirements.

Basic azimuth and elevation scans are shown in Fig. 16. The large circle represents the diameter of Dragonfly's flat side. The smaller grayish circles are the hot spots (0.9 mm in diameter) associated with various azimuth and elevation

Fig. 11 A basic Dragonfly sensor using a relay lens.

Fig. 12 Illustration of what a more compact system might look like.

Fig. 13 Angular profile scanner.

Fig. 15 Directional calibration station. Centered collimated beam comes in from the right. (Collimator not shown).
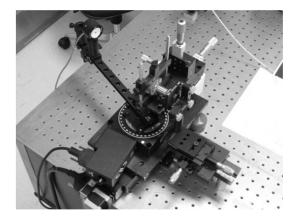
input angles. The small red dot in the middle of each hot spot circle is the centroid. It is the location of this centroid that connects a pixel to a specific direction. Currently, a centroid shift of 1 pixel corresponds to 0.1 deg.

A complete raster scan can and has been done. However, this does not conform to the natural polar coordinate system of the Dragonfly optic. A more visually meaningful data presentation showing contours of elevation and radial lines of azimuth is shown in Fig. 17. This data is for Prototype#2. This type of information will be very useful for refining the fabrication process.

5.3 *Spectral Transmission Station*

The purpose of this station is to measure Dragonfly spectral transmission. This requires two measurements which include the incident power on the convex surface aperture and the transmitted power through Dragonfly. Figure 18 shows the latter case. Here, the convex side of Prototype#3 is placed directly against the input port of an integrating sphere (whose external shape is cubic). White light from a Collimator is focused onto the Dragonfly flat side (represented here by the laser spot). Light diverges from the convex side into the integrating sphere. An Ocean Optics spectrometer (whose software is resident on the lab computer) measures the homogenized light emerging from the integrating sphere. The ratio of transmitted to incident power yields transmission. A sample data plot is shown in Fig. 19.
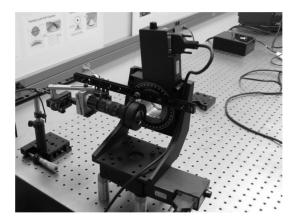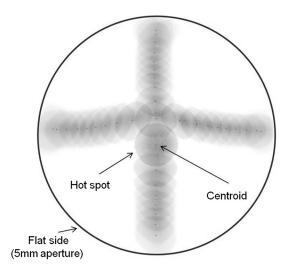
5.4 *Relative Illumination Falloff Station*

As the Dragonfly optic is scanned through its FFOV, the transmitted power passing through the system decreases as the scan angle increases. This is called relative illumination falloff or RIF. For the RIF measurement, we make use of the DCS station in Fig. 20. Collimated white light source is shown toward the bottom. The rear end of Dragonfly is

Fig. 16 DCS azimuth and elevation scan data. Red spot denotes centroid location which ties pixel to a specific direction. The blue circle is the boundary line representing the size of the flat side.
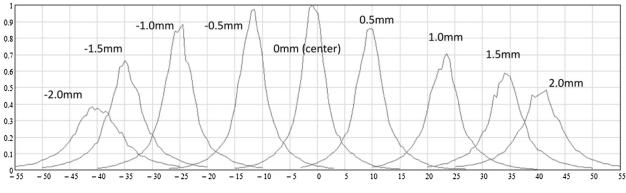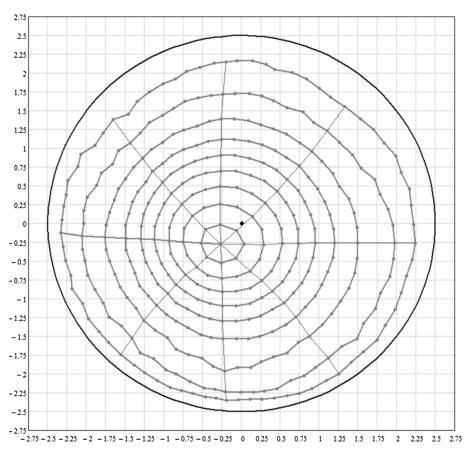

Fig. 14 Example of APS data plots.

Fig. 17 Measured hot spots for rings of constant polar angle from 0 deg to 45 deg in 5 deg increments. The solid black circle shows the location of the edge of the flat face, while the black dot shows the location of the center of the flat face. The red dots show the location of the measured hot spots with the rings connecting locations of constant polar angle and the lines connecting points of constant azimuth angle.

inserted directly into the entrance port of an integrating sphere. A detector is attached to the output port.

Figure 21 shows a preliminary RIF plot for Prototype#2. Ideally, this plot should be rotationally symmetric with the highest value in the center, however, the data shows a bias to one side. We suspect this could be another indication that the aperture center of the prototype is not coincident with the true vertex of the convex surface as illustrated in Fig. 17. This requires further investigation.
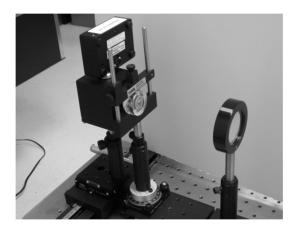

Fig. 18 Spectral transmission station.

5.5 *Radiometric Calibration Station*

The purpose of the RCS, in Fig. 22, is to develop a lab-based reference plane whose irradiance is both known and variable and can be directly related to range-based radiometric measurements.

The orange box at the top (left of center) is the variable white light source. A fiber optic cable (black) connects this source to a microscope objective which focuses the light onto a large core multimode optical fiber (red). Between the objective and the fiber, sits a movable 770 nm spike filter. The MM fiber conveys the light to the focal plane of an achromat (bottom right) which serves to collimate the light. Between the fiber output and the achromat, sits a Uniblitz shutter which simulates a munitions flash duration. The irradiance/energy of the collimated beam is measured by an IL1700 radiometer system from International Light Technology. The detector shown (bottom middle) is either an SED033 or an SHD033. Once the irradiance/energy is measured, the detector is removed and the Dragonfly system (bottom left) is moved up to take its place in the measurement plane.

5.6 *Microscope Inspection Station*

This station, shown in Fig. 23, is used to measure fiber sizes and hot spot diameters on both the convex and flat surfaces of the Dragonfly optic. It is also used to inspect fabrication
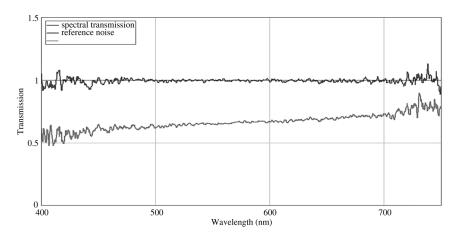
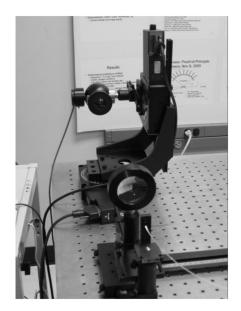**Fig. 19** Sample Dragonfly spectral transmission shown in lower plot.

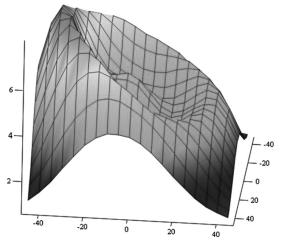**Fig. 20** Relative illumination station.
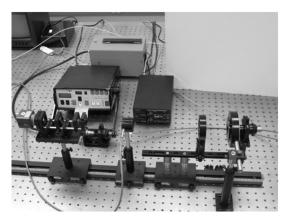

Fig. 21 RIF map of prototype #2.

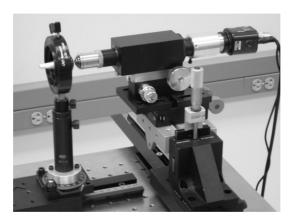**Fig. 22** Radiometric calibration station.

Fig. 23 Microscope inspection station.

flaws such as dislocations. A CCD camera can be attached to the microscope. Hard-copies of the microscope images can be obtained when the CCD output is connected to a video printer. The micrograph, shown in Fig. 4 (on the right side), was obtained using this system.

6 Discussion

This largely empirical paper has introduced the Dragonfly concept, its physical embodiment, sensor structures, and

laboratory techniques for characterization and calibration. Dragonfly is built upon existing coherent fiber optic array taper technology whose principle use is image transfer from one surface face of the taper to the other. However, Dragonfly is not an imager in this sense. Its unique design makes it a directional tracking sensor (as opposed to a fly's eye configuration[3–5]). As you might imagine, there are many potential military and civilian application areas for Dragonfly. Yet, as an emerging technology, there are many interesting aspects that still need to be addressed. For example, we would like to increase the FFOV but, at the same time, decrease the NFOV in order to improve both angular coverage and angular resolution. We would like to further reduce cross-coupling between fibers to improve S/N. To make a more compact and robust sensor would require, reliably, mating an FPA chip directly to the Dragonfly flat side. It would be very beneficial if an optical model of the Dragonfly optic could be built to predict performance and examine design tradeoffs. There are potential applications for Dragonfly, in 3 to 5 μm spectral region, if transmissive materials compatible with the Schott's fabrication techniques can be found. Then, there is the question of range. Dragonfly, by itself, cannot provide range unless something is known about the radiometric behavior of the source. However, two Dragonflys on the same platform, with a known separation between them, can then use triangulation to determine range. How well this can be done remains to be seen. As you can see, there is still plenty of interesting work lying ahead.

Acknowledgments

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1. The Dragonfly concept is the intellectual property of UAHuntsville. Invention Disclosure March 2004. UAHuntsville Invention Disclosure January 2011, Utility patent application (January 2012).
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Joe Geary received his BA in physics from LaSalle College in 1966. He received his MS and PhD in optics from the University of Arizona Optical Sciences Center in 1975 and 1984, respectively. He has 46 years of broad-based experience in optics. He has been with the Center for Applied Optics at UA Huntsville since 1996 where he is a research professor. He has authored 43 papers in referred journals, written four books, and holds ten patents.

Lisa Blackwell received her BA in physics from Auburn University in 1994. She started her graduate work in 1996 at CREOL at the University of Central Florida. In 1997, she moved to UA Huntsville and received her PhD in optical science and engineering in 2001. Immediately following, she joined the staff of the Center for Applied Optics as a Research Scientist. At the CAO, she has performed work in a wide variety of areas in optics including design, analysis, and optical testing.

Tim Edwards received his BS in mechanical engineering from Duke University in 1976, and his PhD in electrical engineering from the University of Memphis in 1996. He has worked sensor systems for Night Vision Labs (NVL), Army Test and Evaluation Command (ATEC), and AMRDEC. His sensor work began in 1980 with the development of the production line assembly and test stations for the Apache Fire Control system (TADS/PNVS). He is currently the projects lead in the Current Operations Group at the Aviation and Missile Research, Development, and Engineering Center at Redstone Arsenal (Huntsville, Alabama).

Mike Dargie received his BS in mechanical engineering from Central New England College in 1976 and his MBA from Western New England College in 1983. He is currently the senior project manager in the New Product Development group with Schott North America, Inc. Southbridge, Massachusetts. He has worked in imaging fiber optics, both fused and flexible, for more than 35 years. He is experienced in all aspects of fiber manufacturing, processing, and optical finishing. He has served in roles which include manufacturing engineering manager, QA manager, and senior applications engineer. His current focus is on new applications for both the defense and medical markets.