DOE/NV/25946--1532
LA-UR 12-22911

A fisheye lens as a photonic Doppler velocimetry probe

Brent C. Frogget*[a], Brian M. Cata[a], Brian C. Cox[a], Douglas O. DeVore[a], David L. Esquibel[a], Daniel K. Frayer[a], Michael R. Furlanetto[b], David B. Holtkamp[b], Morris I. Kaufman[a], Robert M. Malone[a], Vincent T. Romero[a]

[a]National Security Technologies, LLC, P.O. Box 809, Los Alamos, NM USA 87544
[b]Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM USA 87545

ABSTRACT

A new fisheye lens design is used as a miniature probe to measure the velocity distribution of an imploding surface along many lines of sight. Laser light, directed and scattered back along each beam on the surface, is Doppler shifted by the moving surface and collected into the launching fiber. The received light is mixed with reference laser light in each optical fiber in a technique called photonic Doppler velocimetry, providing a continuous time record.

An array of single-mode optical fibers sends laser light through the fisheye lens. The lens consists of an index-matching positive element, two positive doublet groups, and two negative singlet elements. The optical design minimizes beam diameters, physical size, and back reflections for excellent signal collection. The fiber array projected through the fisheye lens provides many measurement points of surface coverage over a hemisphere with very little crosstalk. The probe measures surface movement with only a small encroachment into the center of the cavity.

The fiber array is coupled to the index-matching element using index-matching gel. The array is bonded and sealed into a blast tube for ease of assembly and focusing. This configuration also allows the fiber array to be flat polished at a common object plane. In areas where increased measurement point density is desired, the fibers can be close packed. To further increase surface density coverage, smaller-diameter cladding optical fibers may be used.

Keywords: photonic Doppler velocimetry, PDV, fisheye lens, single-mode fiber

1. INTRODUCTION

Engineers are often asked to create innovative solutions when our clients' application requirements change. This has recently been the case with the dynamic measurement of imploding surfaces. Increased numbers of channels, continuous time measurement, and small cavity encroachment were desired. Fortunately, fiber-optic data transmission devices from the telecommunications industry are coming to the rescue.

A recent diagnostic method that grew from the latest developments in fiber-optic data communications is photonic Doppler velocimetry (PDV). PDV uses light scattered from a surface to continuously measure the movement of that surface.[1] This Doppler measurement is similar to that used in lidar to make atmospheric wind measurements. The Doppler-shifted light from the moving surface is beat against unshifted light to create fringes in a Michelson interferometer made up of fiber-optic components. A fiber-optic circulator is used as the beam splitter of the interferometer. Reference (unshifted) light is provided through mixing with an external reference laser source or from back reflections in the probe itself. Surface velocities between a few millimeters per second up to 14 km/s have been measured with further development expected to reach higher velocities soon.[2,3] These measurements have commonly been done at flat surfaces with a bare, single-mode optical fiber or a fiber at some distance using a lens to direct the light. A PDV probe lens or bare fiber can both transmit and receive the laser light. Typically, 1550 nm telecommunications wavelength continuous-wave (CW) fiber lasers, fiber devices, detectors, and digitizers are used.

*froggebc@nv.doe.gov; phone 1 505 663-2015; fax 1 505 663-2003; nstec.com

Interferometry XVI: Applications, edited by Cosme Furlong, Christophe Gorecki, Erik L. Novak, Proc. of SPIE Vol. 8494, 84940D · © 2012 SPIE · CCC code: 0277-786/12/$18 · doi: 10.1117/12.930195

A new requirement is to use PDV to measure a curved imploding surface at multiple points. These dynamic material experiments frequently involve complicated geometries so that large numbers of data points are a distinct advantage. Electrical shorting pins of various lengths were used previously to make such measurements.[4] An example array of electric shorting pins is shown in Figure 1. An electrical pin provides a shorting signal when its tip comes into contact with the surface. Each electrical shorting pin gives a single timing point of the surface collapse. Each length of a pin records one distance, so that many different lengths of pins are needed to follow the movement of an imploding surface. However, longer pins can interfere with the surface movement to be measured by shorter pins. A dense array of pins at many lengths are also needed are needed to map a surface. New PDV optical technology greatly increases data return in such measurements.

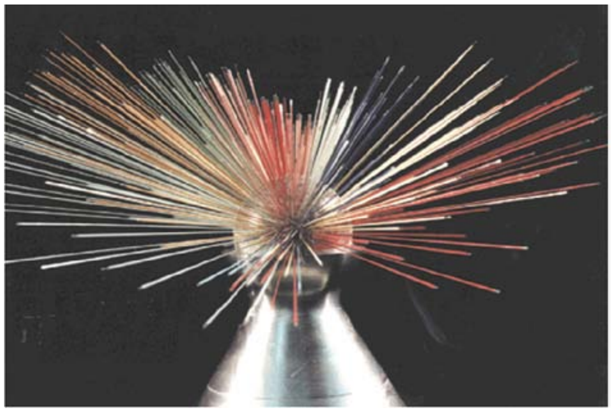

Figure 1. An example array of electric shorting pins of different lengths to measure an imploding surface[5].

To support a greater number of measurement tracks, recent work has been done to record the data by multiplexing the PDV signals.[6] Software development is also progressing for analysis of the many data channels obtained.[7]

Several different optical designs were investigated to measure the concave surface. Individual collimated optical probes using graded-index lenses coupled to optical fibers were first used to prove the continuous tracking of the concave surfaces. These can be arranged in a ball shape that is small compared to an array of shorting pins. In 2010, a probe was designed in a ball shape with discrete fiber collimators pointed toward the surface of interest. This discrete collimator multipoint ball probe is shown in Figure 2. As the number of points is increased, however, this probe eventually comes to its limit in how small the entire group can be made while still having reasonable optical fiber bending radii.

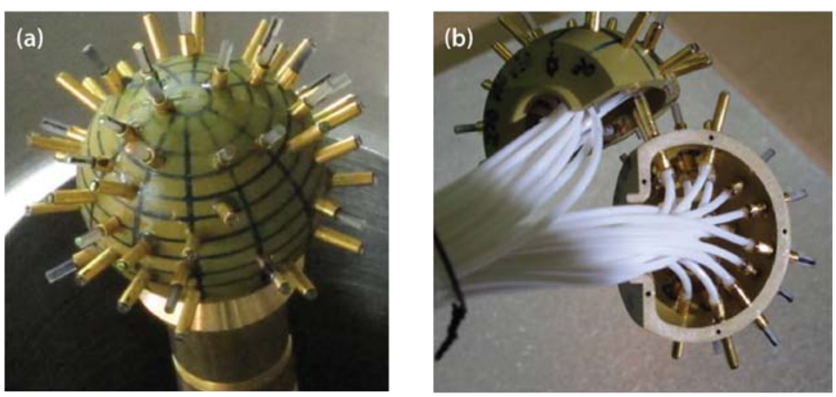

Figure 2. Discrete collimator multipoint ball probes: (a) assembled discrete ball probe and an (b) opened discrete ball probe showing large jacketed fibers. Even with smaller jacketed optical fibers, there comes a limit to how many points can be added in a small package size. Photos by Dean L. Doty, LANL.

Imaging is an efficient way to collect the many individual data points into individual optical fibers from a target surface. To keep encroachment at a minimum into the cavity by the probe, an eyepiece lens design with an external pupil was investigated. This eyepiece lens works well over a limited angular range. Eventually, as angular coverage nears 90 degrees from the lens axis, the lens elements almost wrap around the pupil so that seeing on one side of a hemisphere interferes with seeing on the other side. Designs using curved reflective elements were also considered, but these had the same wrap-around problem as the eyepiece lens design. But, in our new design, some encroachment past the center of the cavity would be necessary in order to measure beyond 90 degrees from the probe axis.

In order to view multiple parts of a concave surface at or beyond 90 degrees from the lens axis, a multi-faceted prism with seven imaging lens stacks was made.[8] The multiple lens array probe is shown in Figure 3. The miniature lens stacks were arranged in a six-around-one configuration. This design used a six-faceted reflective pyramid prism to reflect light from the outer lens stacks with a hole in the center for the center stack straight-through light. The external pupil for each lens stack was very near the prism reflective faces. The prism faces could be angled to different parts of the surface to be measured. Many points can be measured in each region; however, there are gaps between the different regions where the surface is not measured.

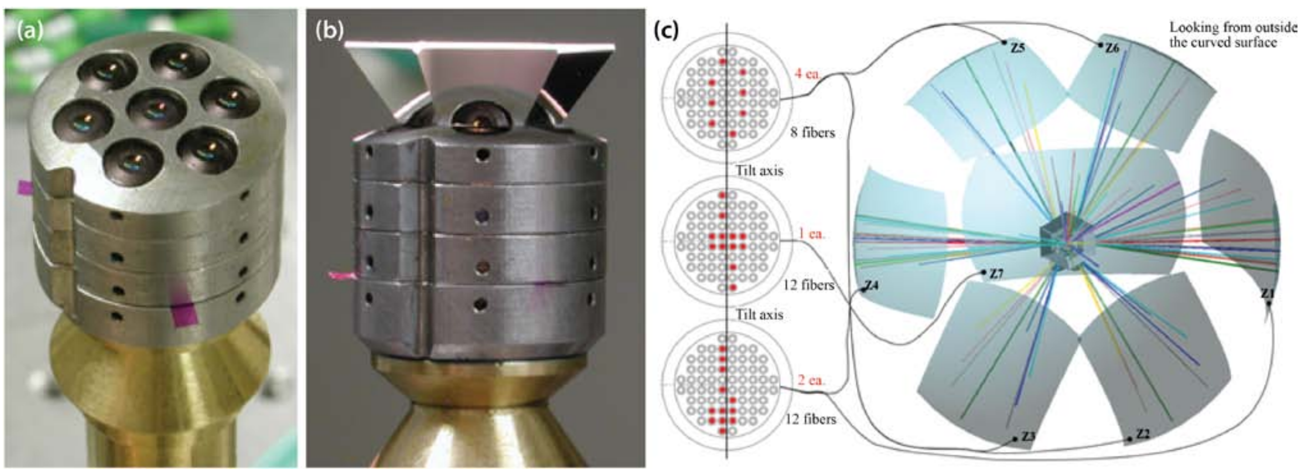

Figure 3. Multiple lens array probe. (a) without multi-faceted prism, (b) with prism, (c) fiber points in zone coverage (zone positions can be changed if prism face angles are changed). Photos by Robert M. Malone.

Ultimately we designed a third type of lens, the fisheye lens that is the subject of this paper. It is described in detail in the following sections.

Recently, a series of dynamic PDV tests within hemispherical shells were fielded using a discrete collimator multipoint ball probe, a multiple lens array probe, and a fisheye probe design (described in the next section). All three gave comparatively high-quality data. The fisheye lens' performance stood out over its companion probes in several ways. First, the fisheye element does not encroach much into the center of the imploding hemisphere. This is important because experimentalists ideally want the measurement to record data until the shock wave impacts the probe; therefore, the smaller the probe the better it will record late-time information. Second, the physical size of the waist near the center of the cavity is smaller. This helps to get the probe through a small opening for blast mitigation. Third, angular coverage can be more complete. Fourth, the fisheye probe is relatively easier to assemble than other multipoint probes.

2. PDV FISHEYE PROBE OPTICAL DESIGN

To image over a very wide range of angles a fisheye lens is used. The 'fisheye' term refers to simulating the distorted, near-180-degree, large angular view that fish have of the world, a result of the light deflection that occurs as light travels through the air-to-water index of refraction change. This lens type produces a whole-sky image as a finite circle. Beyond Brewster's angle, at the water-to-air interface, a fish would see a reflection, whereas some fisheye lenses 'see' beyond 180 degrees with darkness beyond their limit.

To keep costs low, the PDV recording system uses components that are standard to the telecommunications industry. The most common components use light in the 1550 nm band, including CW fiber lasers and amplifiers, detectors, optical isolators, splitters, combiners, and optical fiber attenuators. Therefore, the fisheye lens for PDV was designed for operation at the 1550 nm wavelength. Glasses for high transmission in this region were chosen. Some effort to reduce chromatic aberration and extend the band to visible red light was also made, but was not emphasized.

The first really wide-angle, or panoramic, lens imaged onto a curved film plate.[9] A curved image plane is very inconvenient for mounting an array of optical fibers. Just like the eyepiece lens and reflective lens designs, the panoramic lens type also has the problem of wrapping around near 90 degrees from the lens center axis as angular coverage is increased. More recent wide-angle and fisheye lens designs use more elements to image onto a flat plane. However, off-axis field points for those designs come into the image plane at a significant angle, as shown in Figure 4. To get maximum light signal coupled both out of and back into the optical fibers, the optical fibers would have to be mounted at different angles across the image plane. That would make fabrication and assembly more time consuming. Therefore, a requirement for this design was to make the image light telecentric so that off-axis field points (or optical fibers) are normal to the image surface.

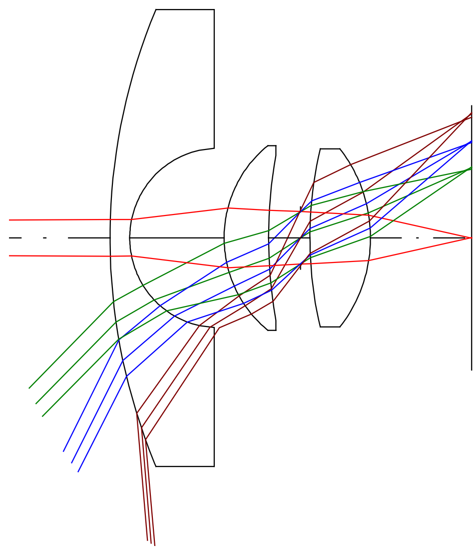

Figure 4. Example fisheye lens showing off-axis points at angles to the image plane. Optical fibers would have to be mounted at different angles across the image plane to transmit and receive that light.

For greater reference light flexibility in PDV, external laser sources are mixed with the Doppler-shifted signal. This requires that back reflections from the probe lens elements and the optical fiber itself be minimized. Good anti-reflection coatings for glass-to-air interfaces and the use of a minimum of lens elements are important for the operation of the external reference light. One way to do this is to angle-polish the optical fibers as was done for the multiple lens array probe. However, the angle polish changes the pupil angle coming out of the optical fiber, and assembly of individual angle-polished optical fibers with a common angle direction was tedious. To keep back reflections at the optical fiber ends to a minimum, this design uses an index-matching, fused silica lens element in contact with the fibers. The index-matching lens element performs the multiple duties of keeping back reflections low, bending the light to be telecentric out of and into the optical fibers from the rest of the fisheye lens, and flattening the image plane. The index-matching element and optical fiber array can also be adjusted as a unit for fine focusing.

3. OPTIMIZATION

The lens was modeled by tracing from a spherical surface through the lens to the fiber plane with all field points weighted equally. This method optimized imaging at 1550 nm from the large to the small conjugate side. Analysis was later performed with the lens model flipped to trace from the fibers to the spherical surface. A simple example fisheye lens was used as a starting point. Due to inherent fisheye lens barrel distortion, magnification is not constant across the field. Therefore, the numerical aperture of the outer field points was larger than that of the center field points. To address this, vignetting factors were employed so that the outer field points would not made a light cone excessively large for a standard single-mode optical fiber. As optimization progressed, adjustments were made to the vignetting factors of these outer field points.

Merit function weighting was high for the 1550 nm wavelength. Weight was also entered to make each field point normal to the image surface. A small weight was set to minimize the incident angle of light on the first surface. Glasses were initially allowed to vary, but were later fit to the model. A short lens effective focal length helped for small beam diameter channels and reduced physical size. A trade-off in the overall magnification or size of the optical fiber plane versus point-to-point resolution on the surface is made.

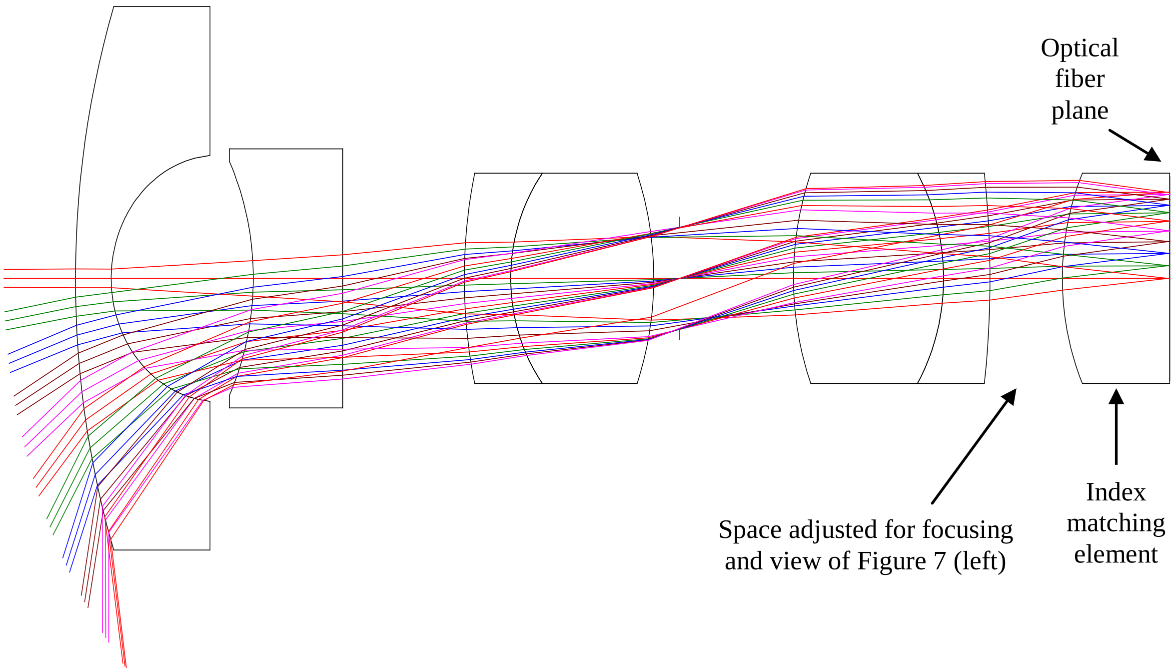

Figure 5. PDV fisheye lens ray trace with field points every ten degrees.

Later, commercial off-the-shelf (COTS) elements were chosen for this design. However, because of packaging constraints, most of these elements had to be edged down to fit into the small experiment blast tube. The tolerances of the COTS elements were evaluated to be adequate with the last air space used as a compensator. The optical ray trace is shown in Figure 5.

4. ASSEMBLY

The optical fibers are spatially positioned by being mounted into holes in an optical fiber ferrule. The optical fibers are bonded into the ferrule and then the ferrule and optical fibers are polished together. To compensate for imperfections in contact across the fiber ferrule, index-matching gel is added for better coupling at the fiber-to-lens surface.

Commercial optical fiber ferrules for MT connectors are made of glass-filed polyphenylene sulfide (PPS) based thermoplastic. We tried PPS, Macor, Vespel, Torlon and Photoveel II[10] for our ferrules. We found Photoveel II to be excellent for the micro-hole drilling used to spatially position our single-mode optical fibers. It gives clean, burr-free holes at 125-micron diameter. It also polishes well with the optical fibers. Good flat polishing is important to ensure good coupling with the index-matching element. Photoveel II is a fine-grain, machinable nitride ceramic that is used in the probe card industry. Figure 6 shows a ferrule stuffed with optical fibers prior to cutting and polishing. 12-fiber ribbons were used with MT connectors for reduced connector count.

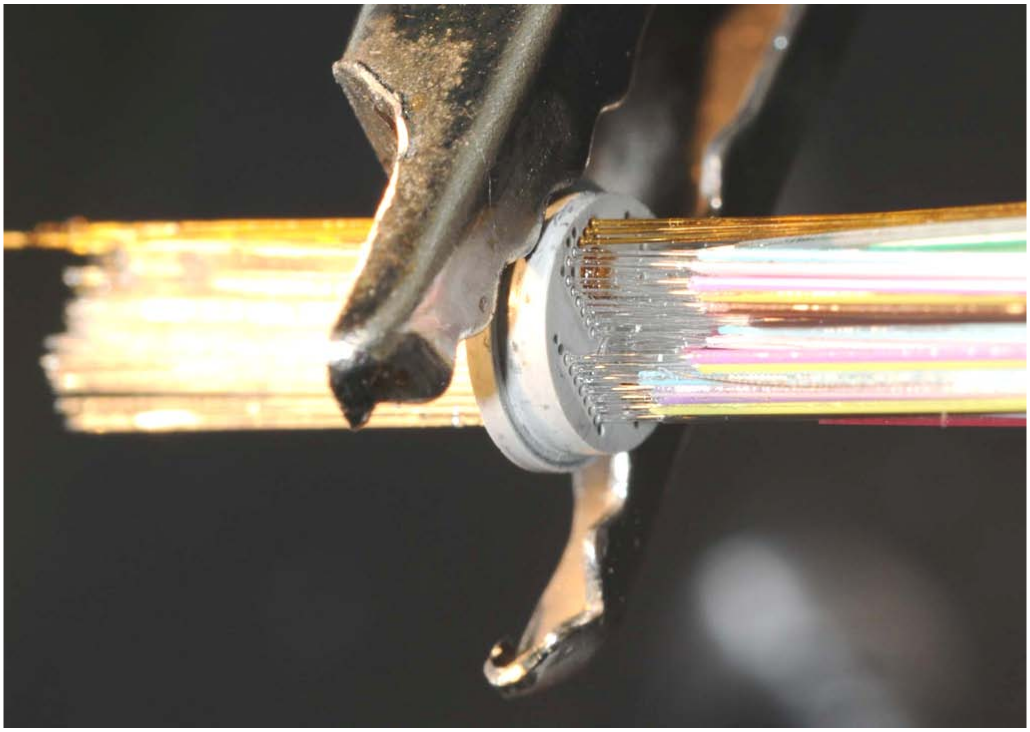

Figure 6. Fiber ferrule stuffed with single-mode optical fibers before fibers were cut and polished. Photo by Brian C. Cox.

When the fisheye lens is assembled, the fiber ferrule and index-matching element with index-matching gel are bonded together as shown in Figure 7 (left). (We had tried using index-matching epoxy, but had better success with index-matching gel.) After the other lenses are glued into the housing, the index-matched lens/fiber-array unit is moved to the proper distance for fine focusing of the fiber beams using an infrared camera. The assembled unit is shown in Figure 7 (right). If the unit needs to be inserted into blast hardware, that can be done at this point with the focus distance determined and then glued into place.

Figure 7. Fisheye probe assembly. Fiber ferrule bonded to index-matching element (left). Assembled unit (right). Photos by Vincent T. Romero and Brian C. Cox.

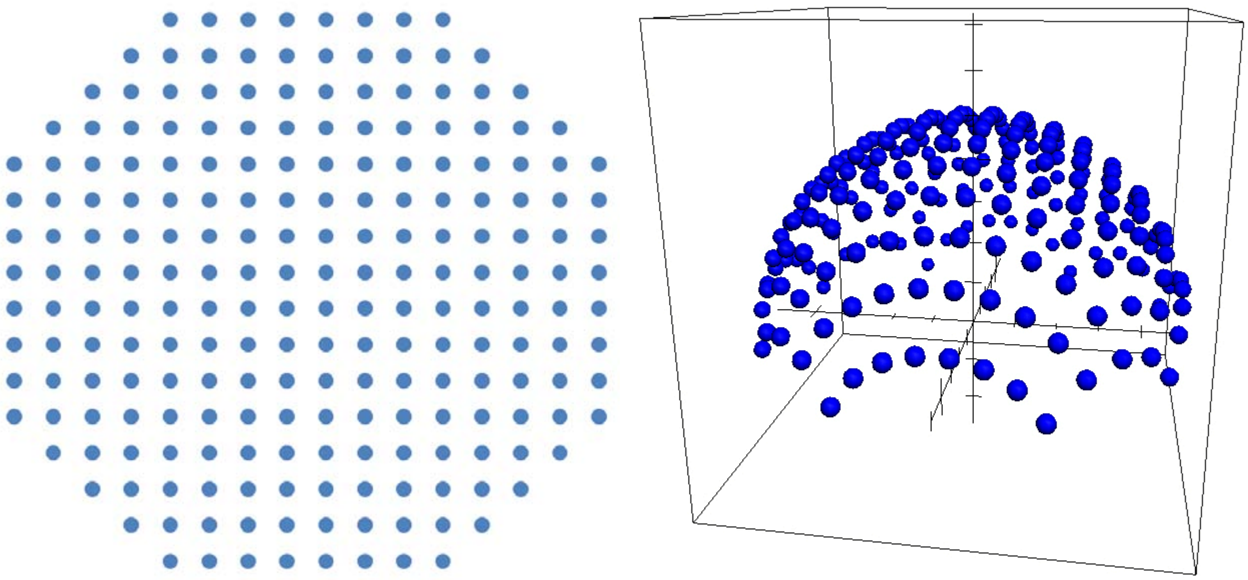

Figure 8. Example channel map of 216 points past 90 degrees from lens axis hemispherical coverage (channel circles not to scale). (left) Ferrule hole layout; (right) modeled 3-D map of points projected onto a hemisphere. Denser channel coverage and other patterns can be made.

After assembly the beam direction angles of the optical fiber channels through the probe are measured at the 1550 nm wavelength. Channel efficiency and back-reflection measurements are also recorded. In measuring channel efficiency versus distance, a broadband laser source is used to eliminate speckle noise. Figure 8 shows an example channel map with evenly spaced hemispherical coverage of 216 points. Other channel patterns are possible.

5. PDV FISHEYE PROBE IMPROVEMENTS

Inherently, fisheye lens images are distorted. The distortion manifests itself as pincushion distortion when going from the optical fiber plane to the curved surface and as barrel distortion when going from the curved surface to the optical fiber plane. The points at higher angles in Figure 8 are spread out more than those at lower angles. This change in magnification versus field angle causes elliptical optical fiber spots on the concave surface at high angles. It also manifests itself as a loss of efficiency for PDV signals at the higher angles. High incidence angles on lens elements at high angles may also have less effective anti-reflection coatings.

Further work has improved the fisheye lens probe’s design performance. Global optimizations with merit functions that emphasize telecentric light at the optical fiber plane, good imaging, and minimizing magnification differences across the image field were performed to increase efficiency at the higher angles. Again, a small weight to minimize the outer surface incident angle was set. Figure 9 shows modeled illuminance projections of an optical fiber onto the inside of a hemisphere at 0, 60, and 90 degrees from the lens axis for the current design (left) and an improved design (right). The improved design has rounder optical fiber spots at the higher angles.

Plots of the optical fiber position verses angular position in a hemisphere are shown in Figure 10. The distortion is the difference between the linear fiber position and the model fiber position. The plot shows how further optimization has decreased the distortion in the improved design. A ray trace drawing of the improved design is shown in Figure 11. Notice the high-angle point fiber spacing and beam size improvements.

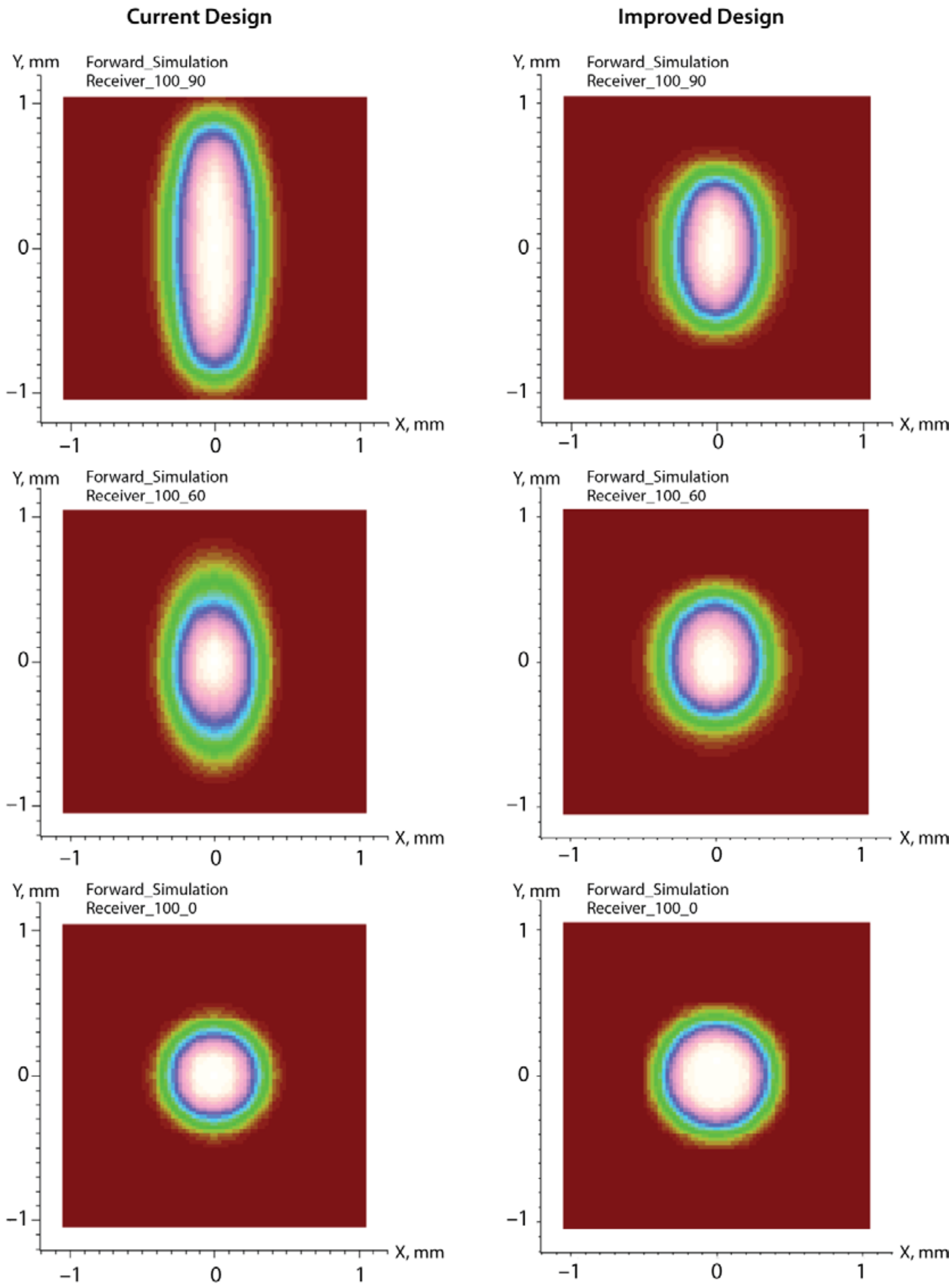

Figure 9. Modeled illuminance projections of an optical fiber inside a hemisphere. From top, rows are 90, 60, and 0 degrees from the lens axis. Shown are the (left column) current design and the (right column) improved design. Notice the elliptical spots at 90 degrees.

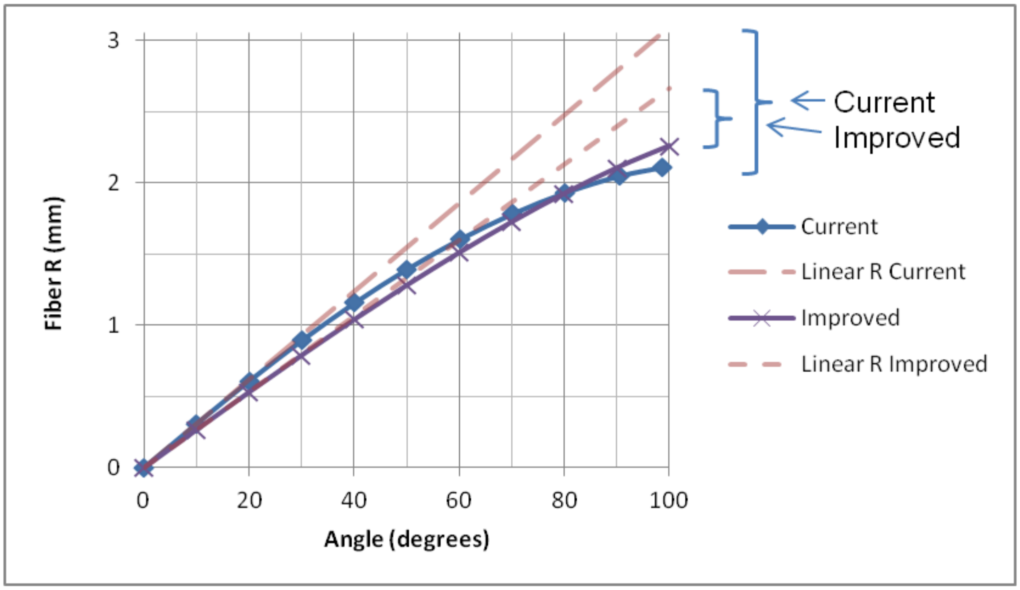

Figure 10. Plot showing reduced distortion for improved fisheye lens probe.

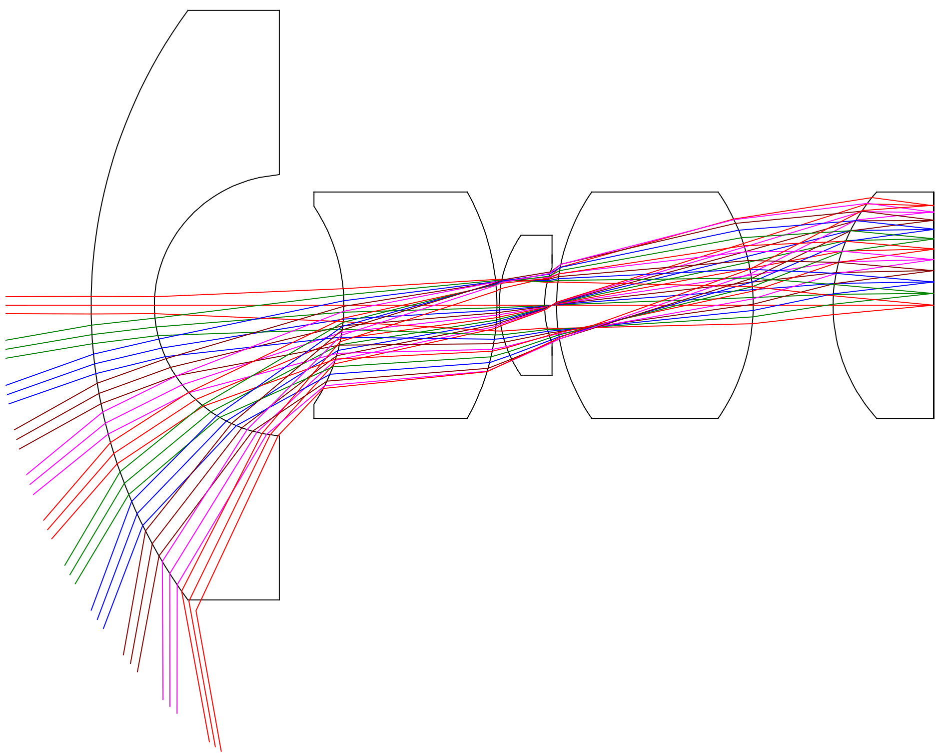

Figure 11. Ray trace of the improved PDV fisheye lens shows reduced distortion. (Compare the high angle beam size and fiber separation to that of Figure 5.)

6. CONCLUSION

A fisheye lens has been used with an optical fiber array probe to measure many discrete points on a curved imploding surface. This probe provides a continuous time dynamic velocity record of the surface from initial start until it reaches a small central region. The fisheye probe provides a wide-angle coverage of a concave surface with little encroachment into the cavity. Low back reflection and low distortion improve velocity measurement efficiency. Many points can be measured through the same probe, which with continuous time recording, collects orders of magnitude more position data than has been collected before on experiments of this type. Many different point measurement patterns are possible.

ACKNOWLEDGMENTS

This manuscript has been authored by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of the manuscript, or allow others to do so, for United States Government purposes.

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