Fiber-coupled monocentric lens imaging

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Abstract: Monocentric lenses have proven exceptionally capable of high numerical aperture wide-field imaging - provided the overall system can accommodate a spherically curved image surface. We will present a summary of recent work on the design optimization and experimental demonstrations of monocentric wide-field imaging, including systems based on waveguide coupling of the image to conventional focal plane sensor(s).

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Conventional "fisheye" imagers map wide fields of view onto flat image sensors, but suppressing field curvature imposes harsh design tradeoffs, especially as the focal length grows. Monocentric lenses are the polar opposite. The symmetry in a lens made of concentric hemispherical surfaces cancels most of the geometrical aberrations, and enables high-resolution image formation on a hemispherical image surface [1-2]. Figure 1 shows three designs for a 120˚ field of view and 12 mm focal length lens. At top is a F/2 retro-telephoto lens with good resolution, but substantial bulk. The center design shows a related "compact" design which sacrifices both resolution and light collection. The monocentric achromatic lens below is smaller, simpler, and provides much higher resolution on the spherical image surface. The apparent reduction in aperture area is misleading. Most of the light incident on the larger lenses is blocked by the internal aperture, whereas the smaller lens transmits a uniform fraction of the light, resulting in a lower F/# at all angles. The graph inset at lower left is a familiar bubble-chart of the field of view and light collection for standard flat-field objective lenses [3]. Monocentric lenses open a previously unachievable domain, but the question remains how the image can be recorded, and the stray light blocked, for a spherical image surface. One way is to relay-image overlapping areas of the sphere to planar sensors, using aperture stops in each relay to control stray light, and image processing to fuse the overlapping image boundaries [4-6]. This enables multi-Gigapixel real-time imaging, but the relay optics (e.g., 221 sets for a 2.5Gpix imager) add significant complexity and cost. Here we describe an alternative, using high-resolution fiber bundles for image transfer to planar sensors.

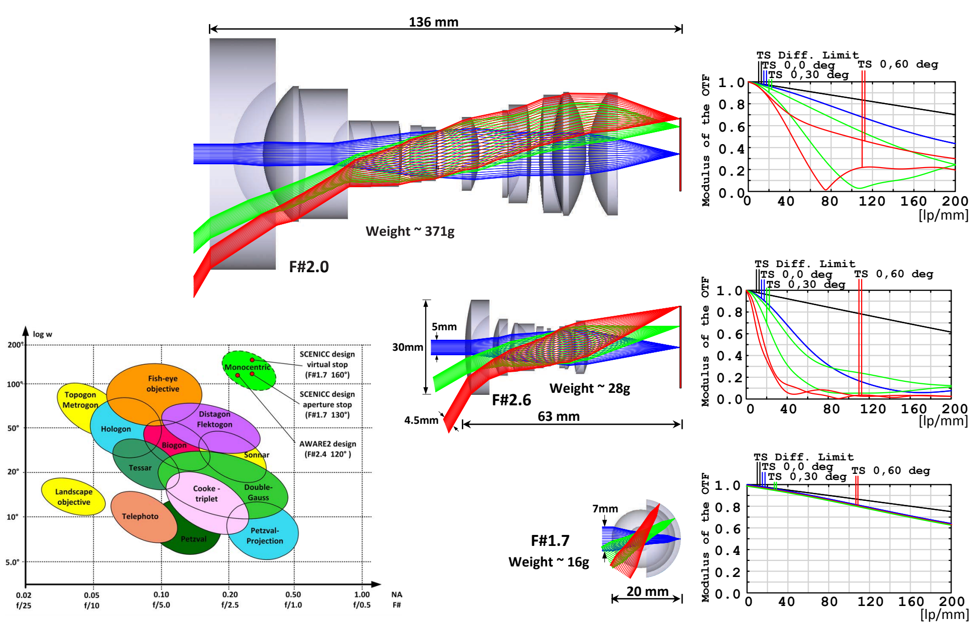

Fig. 1: Comparison of three large numerical aperture 12 mm focal length lenses with a 120˚ field of view, showing the increase in resolution possible with monocentric lenses and a spherical image surface.

The use of a dense array of high-index optical fibers to couple light from one surface to another was explored in the early 1960s [7] and has since been extensively used for medical applications such as endoscopy. Using a curved fiber bundle to interface a monocentric lens was one of the first conceived for this new technology [8], but early bundles were unsuitable due to the low contrast between the core and cladding indexes. Avoiding crosstalk between the low numerical aperture fiber cores required wide spacing, yielding poor resolution and transmission efficiency. Modern fiber bundles from Schott fiber optics have a core and cladding index of 1.81 and 1.48, incorporate index-matched absorptive glass to suppress cladding modes, and can be drawn to an extremely fine pitch. Figure 2 shows the structure and crosstalk measured for a 2.5 µm pitch bundle with transmission losses dominated by surface reflections, and crosstalk limited to the nearest neighbor fiber (for low to moderate divergence light).

A full-field fiber-coupled imager can use multiple bundles cut to divide the field into adjacent regions with uniform coupling over a limited (~30˚) field. The initial demonstration of a fiber coupled monocentric lens is shown in Figure 3. A single bundle was attached to a Omnivision backside illuminated CMOS sensor with 1.75 µm pixels and a Bayer color filter. The opposite surface was ground to match the 12 mm image surface radius of the two-glass monocentric lens from Figure 1 [9], attached to the lens with index-matching gel, and moved to acquire different image fields. The result is shown in Figure 4. At far left, the image acquired by a F/4 wide-angle EF zoom lens on a 21 Mpixel Canon EOS 5D MkII is cropped and zoomed to compare with the image from the monocentric lens, acquired by relay imaging onto a high-resolution microscope, to the Omnivision sensor, and using fiber coupling to the same sensor. Other than color artifacts due to the lack of an IR cut filter, the F/1.7 monocentric lens provided equivalent or better performance in approximately 25x smaller volume than the F/4 reference imager.

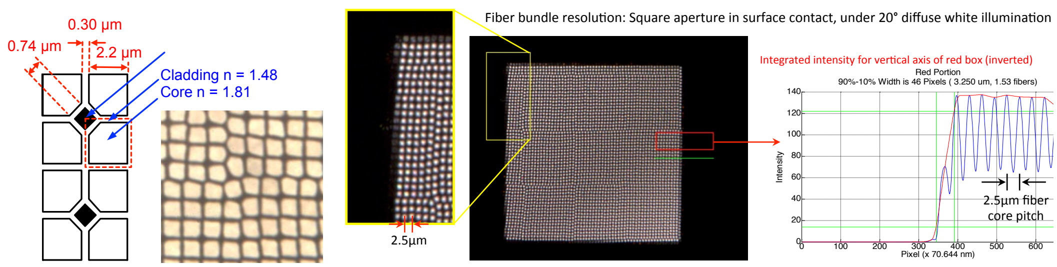

Fig. 2: Schott 2.5 µm pitch 5-sided fiber bundle material (left) and spatial resolution for step function illumination (right).

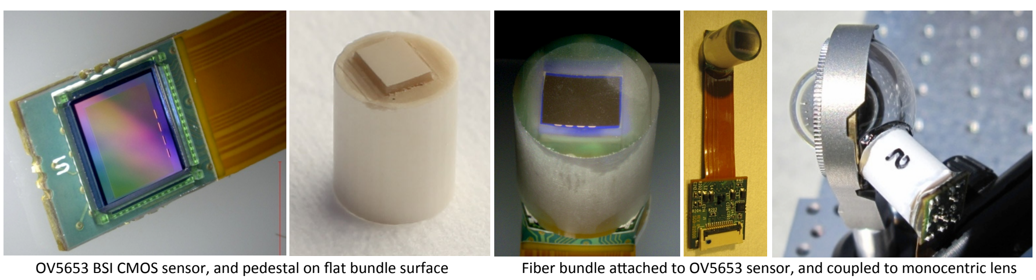

Fig. 3: Fiber bundle coupling between a conventional CMOS focal plane and the prototype monocentric lens.

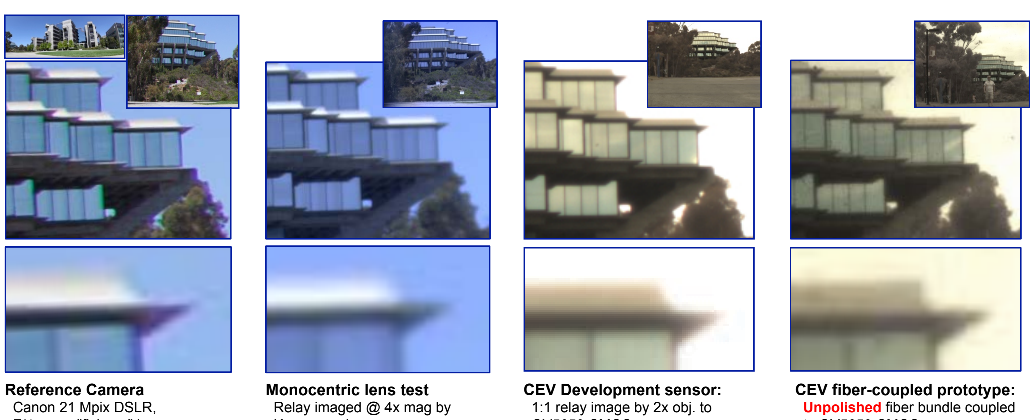

Fig. 4: Performance comparison between a conventional lens (far left) and the fiber-coupled monocentric prototype.

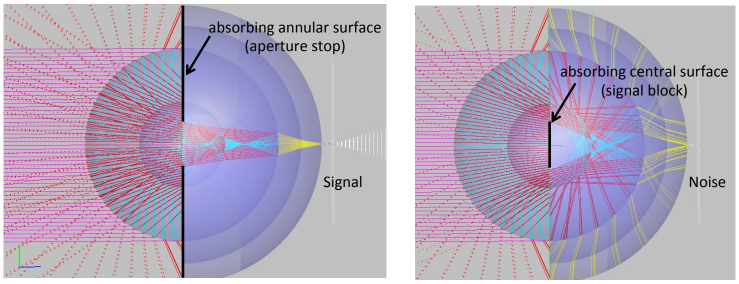

Fig. 5: Signal and noise in a monocentric lens from 1st & 2nd surface reflections.

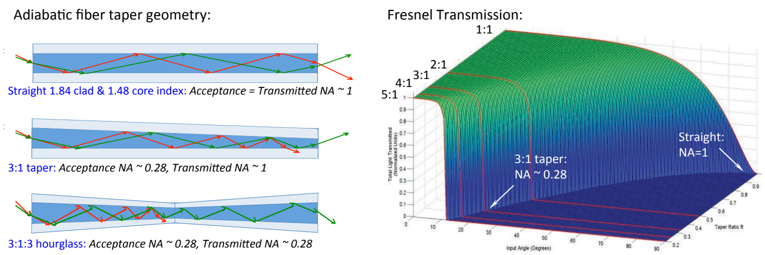

Fig. 6: Fresnel losses in an adiabatic fiber taper enables controlled angle filtering.

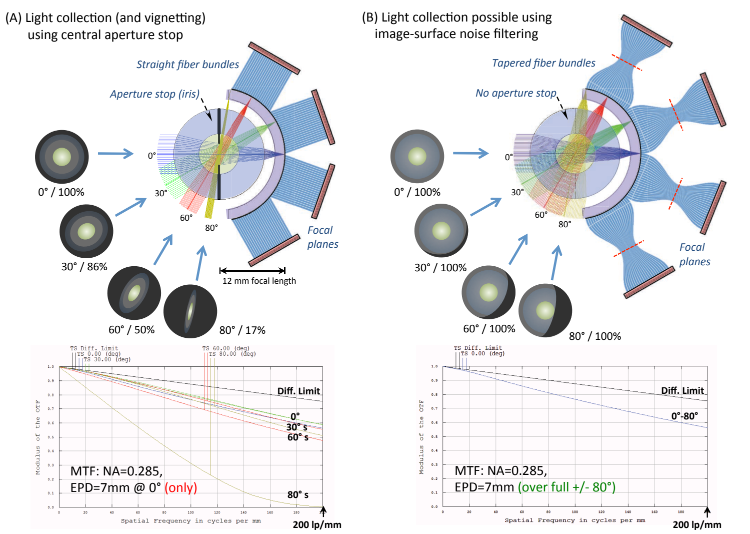

Fig. 7: Image-surface filtering can increase wide-angle performance to approach the fundamental information transmission of the central lens aperture, area / λ^2.

This initial demonstration is only a first step towards fully optimized fiber-coupled monocentric imagers. An end-to-end model of the overall system must include coupling and transmission of light within the fiber, coupling of the transmitted light into the sensor, and digital processing of the detected signal to minimize effects of the fiber sampling. This will allow optimization of the structure of a straight fiber bundle, as well as exotic 3-D fiber structures to provide more than simple transmission.

Monocentric lenses can use a normal aperture stop, but their full potential can only be achieved by allowing light to transmit through an open aperture. An analysis of stray light from aberrations and surface reflections in the F/1.7 lens reveals that the signal and noise can be fully differentiated by angle of incidence on the image surface [Fig. 5], such that a conformal angle-selective filter could provide a "virtual iris" which tilts to follow incident beam angle.

There are several ways to implement this filter. One is mode stripping in tapered fibers, as shown in Figure 6. A simple Fresnel reflection analysis suggests that a 3:1 taper would provide a sharp angle filter matched to the F/1.7 lens, and more accurate scalar field propagation models indicate that a more modest taper can accomplish the same result for fine (~2 µm) fiber pitches. The fiber tapers can terminate at the waist (to minimize volume) or at the opposite face of the hourglass taper (to minimize crosstalk).

Figure 7 indicates the potential of this approach. A single aperture spherically symmetric lens may ultimately collect a diffraction-limited signal over a range of angles so large that useful light is collected even using the back surface of the lens.

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