10.1117/2.1200608.0358

Photon sieve telescope: imaging with 10 million pinholes

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Telescope designers are developing a diffractive optic with millions of holes for future large space-based telescopes.

To continue improving resolution, future space-based surveillance platforms require telescopes with ever-larger diameters. Currently, launch vehicle volume limits the size of primary mirrors that can be transported into orbit. One possible solution is to use membrane apertures that can be deployed from small, lightweight packages. Until now, most research in this area has concentrated on solving the problems of how to create high quality, three-dimensional reflective surfaces in zero or microgravity. Still, the largest surfaces fabricated have surfaces orders of magnitude worse than required for perfect imaging in the optical regime. An alternative solution involves construction of a flat membrane primary that focuses light using diffraction. This enormously simplifies the problem because there is no out-of-plane deformation required, and pulling a sheet flat in zero or microgravity is relatively straightforward. The diffractive element proposed is a photon sieve.

The photon sieve was conceived by Kipp and colleagues,[1] and is based on the well-known Fresnel zone plate, which consists of a series of alternating transparent and opaque concentric circular rings. The photon sieve essentially has the same form, but with the rings dotted with holes. Each hole diffracts light to combine in phase at a location downstream much like a multitude of tiny apertures in a phased array. Kipp and others[1,2] also realized that the hole sizes could be larger than the underlying zone widths. Doing so alleviates one of the big problems with this kind of diffractive optics: the inherently small feature sizes that reduce throughput and are difficult to manufacture.

At the United States Air Force Academy, researchers with the Laser and Optics Research Center (LORC) have developed large photon sieves suitable for telescope use.[3] In this application, photon sieves are superior to Fresnel zone plates because they are made from a single membrane and require no supporting structure. Typical prototypes designed for optical wavelengths have 10 million holes randomly spread in angle over a 100mm-diameter aperture. Typically, the holes range in size from 10 to 200 microns for a 1m focal length primary. The photon sieves made for these experiments are fabricated on chrome-coated quartz plates using electron-beam lithography. Figure 1 shows two images of such photon sieves.

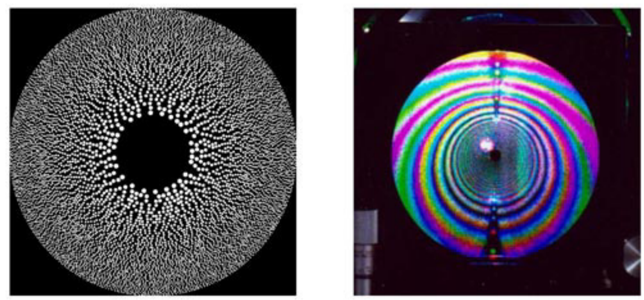

Figure 1. *The central 20% of a photon sieve is shown (left), along with a photograph of the actual sieve lit with red, green, and blue lasers (right). The colorful rings are a Moiré pattern from the underlying circular symmetry.*

Sponsored by the Air Force Office of Scientific Research, the LORC work has led to photon sieves with high-quality focused wavefronts and imaging over an acceptable field of view (see Figure 2). These results demonstrate that the photon sieve is ideal for telescope primaries at least at the design wavelength. But because diffractive elements are dispersive, changing the wavelength dramatically changes the focal length. To overcome that minor limitation, researchers are investigating several solutions. One approach, soon to be published, combines a small secondary holographic optical element with the opposite dispersion characteristics. The final telescope has a bandwidth of 40nm in the visible, making it practical for broadband imaging.

While this technology shows great promise for future space-based surveillance telescopes, there are many other potential applications and designs. For example, the photon sieve lends itself to apodization (shaping) by simply changing the angular or radial density of holes, leading to applications in large space-based

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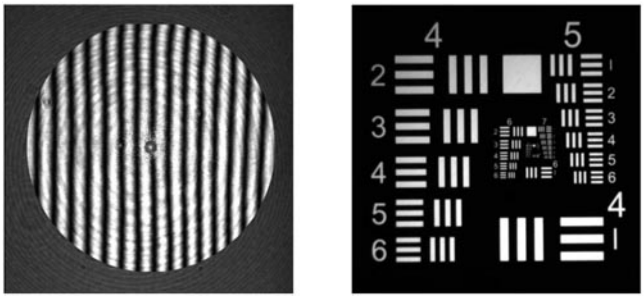

Figure 2. *An interferogram (optical contour map) of a photon sieve indicates a wavefront good to $\lambda/50$ rms (left). The same sieve also demonstrates sharp imaging capability over a useful field of view (right).*

telescopes for exoplanet searches. Another application comes from not requiring all the pinholes to combine in phase to a perfect focus, allowing any arbitrary wavefront to be generated by modifying the underlying conic geometry. This makes it possible to create inexpensive null-correctors that could also be made quite large by patterning thin metal substrates. LORC investigators are looking at both of these approaches. Other groups are investigating photon sieves for photolithography and microscopy at ultraviolet or x-ray wavelengths, and imaging optics for electron beam or terahertz systems.

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Geoff Andersen earned his PhD in physics from the University of Adelaide, Australia. Since 1996, he has been employed as a research associate with the Laser and Optics Research Center, part of the Department of Physics at the US Air Force Academy. His research specialties include holography, lidar, and telescope design. He is a member of SPIE.

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