Micro-optics at the diffraction limit: design for manufacture

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Micro-optics is a well-established field with design criteria that have been validated for diffractive, refractive and hybrid structures. However, these approaches are typically based on the assumption that the optical element is significantly larger than the wavelength of light, meaning that the diffraction effects due to the element's aperture itself can be safely ignored. CMOS image sensors represent an important case where this assumption is no longer accurate (Fig. 1).[1] However, as can be seen in Figure 1, the conventional approach has been simply to shrink the geometry of the microlens used to concentrate incoming light on the active portion of the sensor. Not only does the three-dimensional profile of the microlens become increasingly difficult to fabricate, but the light-concentrating performance is degraded.

A numerical simulation (Fig. 2) shows the dramatic effect the small lens aperture has on the propagation of light to the active region of the sensor. Note the severe chromatic aberration – a consequence of being in the diffractive regime. By taking diffractive effects into account, we find that much simpler, and more easily fabricated structures can perform significantly better.[2] Figure 3 shows an example of one such structure, in which a square block replaces the curved microlens. Intensity enhancements of ≈ 4× versus a typical microlens are obtained. In addition, the light is more effectively confined in the plane perpendicular to the propagation direction, reducing pixel-to-pixel optical cross-talk.

We discuss the design criteria that are applicable to these types of non-imaging microlens concentrators and the impact on their use has on the manufacturing fabrication process flow.

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[1] R. Fontaine, The Evolution of Pixel Structures for Consumer-Grade Image Sensors, *IEEE Trans. Semi. Manf.* **2013**, *26*, 11-16

[2] K. A. Goldberg, US Patent 8,569,678, Micron-Scale Lens Array Having Diffractive Structures

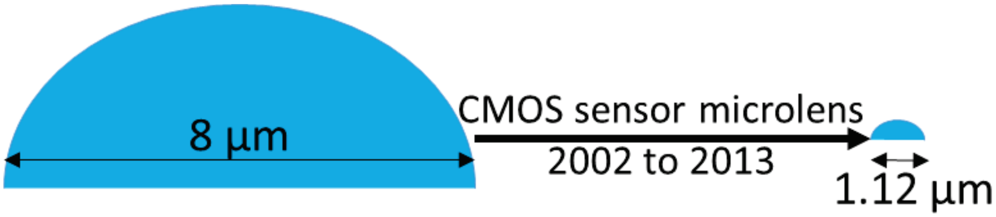

Figure 1: Illustration of how actual image sensor microlens dimensions have evolved over the past decade.

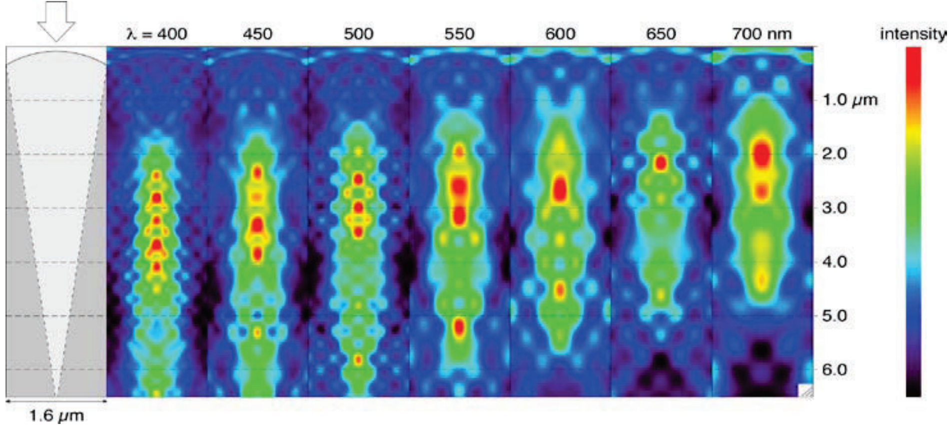

Figure 2. Numerical simulation of three-dimensional light focusing within an individual a spherical-cap microlens with an index of refraction n = 1.3, and a lens radius, R = 1.44 µm. The microlens geometry is shown in the column at left, with light incident from above and the nominal focusing action shown in light gray. Incident wavelengths from 400 to 700 nm, labeled at the top of each column, are considered. The images represent the light intensity in a plane that contains the apex of the microlens; each calculation is individually scaled, and the linear intensity scaling is shown at right.

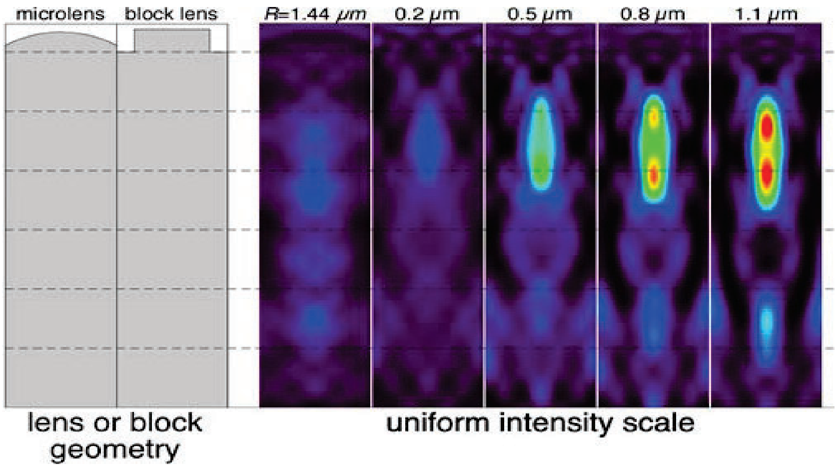

Figure 3. Electric-field intensity cross-section calculations for spherical microlens and rectangular block designs. The individual block heights are given above each simulation case. The cross-sectional geometry is shown at left. Relative to the input field intensity, the peak intensities within the block are (L to R) 2.89 (spherical), 2.84 (0.2-µm block), 7.32 (0.5 µm), 10.38 (0.8 µm), and 11.85 (1.1 µm).