An image sensor with on-die diffractive optics in 0.18µm bulk CMOS

Christopher Thomas, Richard Hornsey
Computer Science, York University, Toronto, Canada

ABSTRACT

On-die optics are an attractive way of reducing package size for imaging and non-imaging optical sensors. While systems incorporating on-die optics have been built for imaging and spectral analysis applications, these have required specialized fabrication processes and additional off-die components. This paper discusses the fabrication of an image sensor with neither of these limitations. Through careful design, an image sensor is implemented that uses on-die diffractive optics fabricated using a standard 0.18µm bulk CMOS process, with simulations indicating that the resulting die is capable of acting as a standalone imaging system resolving spatial features to within ±0.15 radian and spectral features to within ±40 nm wavelength accuracy.

Keywords: CMOS image sensors, microlenses, diffraction gratings, micro-optics, diffractive optics

1. INTRODUCTION AND MOTIVATION

On-die optics have been used in past works to mitigate two significant shortcomings of conventional optical sensor systems: optics package size/complexity, and image sensor fill factor.

Optics package size and complexity are reduced by moving some of the optical components in the system on-die. An example for a non-imaging sensor is the fabrication of on-die reconfigurable gratings by Sagberg et al.1 This replaces what would otherwise be a large, complex optical element. An example for an imaging sensor is the TOMBO microlens array produced by Tanida and Yamada,2 intended to operate without the presence of an external lens.

Image sensor fill factor is important when auxiliary signal processing is integrated into the pixel array.3 This produces an image sensor where only a small fraction of the pixel area is photosensitive. The resulting sensitivity reduction can be offset by fabricating a microlens over each pixel, acting as a concentrator that focuses light on the photosensitive region. An example of this type of device is the sensor fabricated by Furumiya et al.4

While the optics integration methods described in these works are useful, they share a common drawback in that they require non-standard, expensive process steps for fabrication. Refractive optics are typically fabricated via etching of a conformal mold for subsequent deposition5 or by thermal reflow of a patterned resist.6 Diffractive optics are typically fabricated using MEMS processes,7 via custom mask steps to pattern an additional layer added to an existing lithographic process,8 or by laser ablation of the material to be patterned.9

This paper presents the fabrication of diffractive optical elements in a conventional bulk CMOS process, and integration of these elements into both imaging and non-imaging on-die sensors. This fabrication approach is expected to be much more economical than fabrication processes used previously for integrated optics. Section 2 describes the design of the sensors, and Section 3 describes simulated sensor behavior. Characterization data for fabricated sensor devices is forthcoming.

2. SENSOR DESIGN

All of the sensors fabricated had a common design, shown in Figure 1. This design consists of three components: an optical element, a mask, and a photosensor. The optical element is implemented by etching a diffraction grating into a high metal layer. The mask is intended to isolate specific parts of the image resolved by the optical element; it is formed by etching a low metal layer to provide one or more apertures. The photosensor is implemented as a conventional CMOS active pixel sensor, with the photodiode located beneath the image plane mask’s aperture.

All sensors implemented share the following parameters:
The thickness of the mask and optical element grating layers is 0.5 \( \mu \text{m} \pm 20\% \).

- The dielectric in which the sensor is embedded has a refractive index of 2.
- The thickness of the mask and optical element grating layers is 0.5 \( \mu \text{m} \pm 20\% \), but is approximated as being zero.
- Zone plates are optimized for an open-air wavelength of 650 nm (325 nm in the inter-layer dielectric).

Section 2.1 describes the types of sensor under study. Section 2.2 derives first-order equations used to estimate expected sensor behavior. Section 2.3 evaluates the expected performance of imaging sensors (those optimized for angular selectivity). Section 2.4 evaluates the expected performance of spectral sensors (those optimized for wavelength selectivity).

### 2.1. Sensor Configurations

Two types of imaging sensor are used: A Fresnel zone plate, and a wide slit (in lieu of a wide pinhole). These sensor configurations are shown in Figure 2. The Fresnel zone plate has a radius of 5 \( \mu \text{m} \) on its imaging axis (both axes for spherical, one axis for cylindrical). The wide slit is 1.2 \( \mu \text{m} \) wide, imaging in one dimension. This configuration allows imaging via pinhole to be tested while retaining more light gathering capacity than a pinhole aperture imaging in two dimensions would.
Two types of spectral sensor are used: A Fresnel zone plate, and a narrow slit. These sensor configurations are shown in Figure 3. The Fresnel zone plate has a radius of 5 µm, being identical to the version used for imaging. When used for spectral sensing, a fixed incidence angle is assumed, and the intensity of the resulting spot as a function of radius is measured. Chromatic aberration makes this a function of the intensity of incident light at different wavelengths. The narrow slit is 0.6 µm wide. A fixed angle of incidence is assumed, and the intensity of the first diffracted lobe is measured as a function of displacement from the optical axis. The position and size of the first diffracted lobe are wavelength-sensitive, making the lobe’s intensity profile a function of the intensity of incident light at different wavelengths.

2.2. Sensor Behavior Estimation Method

Behavior of Fresnel zone plates as a function of incident light angle $\Theta_0$ and wavelength $\lambda$ is estimated by considering rays passing through three points of a zone plate that is much larger than the incident light wavelength, as shown in Figure 4. Rays passing through the center of the plate are considered to pass unchanged, while rays passing through the edges of the plate are considered to be diffracted by a grating with aperture spacing $d$, as shown in Figure 5a. Behavior of a slit imager as a function of incident light angle $\Theta_0$ and wavelength $\lambda$ is estimated by considering a slit aperture of width $d$, as shown in Figure 5b.

Diffraction of incident light by a grating is reviewed in Figure 5a. The grating aperture spacing is $d$, and the angle of incident light is $\Theta_0$. Apertures are modeled as point emitters. Considering the incident light to be a plane wave, this results in a phase shift $\phi$ between apertures as follows:
Figure 5. Diffraction of light by a) a grating, and b) a slit.

\[ \phi = 2\pi \left( \frac{d}{\lambda} \right) \sin \Theta \]  \hspace{1cm} (1)

Maxima in the angular distribution of light passing through the grating are at angles where wavefronts emitted by successive apertures constructively interfere. Minima are at angles where they destructively interfere. Both are derived using the same equation:

\[ \phi + \pi k = 2\pi \left( \frac{d}{\lambda} \right) \sin \Theta \]  \hspace{1cm} (2)

Taking a first-order approximation for small \( \Theta \) gives:

\[ \Theta = \Theta_0 + \left( \frac{\lambda}{2d} \right) k \]  \hspace{1cm} (3)

Behavior of a slit aperture as a function of incident light angle \( \Theta_0 \) and wavelength \( \lambda \) is reviewed in Figure 5b. The slit diameter is \( d \). Considering the incident light to be a plane wave results in a phase shift \( \phi \) in incident across the slit as follows:

\[ \phi = 2\pi \left( \frac{d}{\lambda} \right) \sin \Theta_0 \]  \hspace{1cm} (4)

Maxima and minima in the angular distribution of light passing through the aperture are described by the following equation:

\[ \phi + \pi k = 2\pi \left( \frac{d}{\lambda} \right) \sin \Theta \]  \hspace{1cm} (5)

Minima occur for even \( k \), where \( k \neq 0 \). This corresponds to cases where for each point in the aperture emitting a ray, a corresponding point on the aperture exists that emits a ray that destructively interferes with the first ray. Maxima occur at \( k = 0 \), corresponding to a plane wave, and at odd \( k \) for \( |k| > 1 \). The second case corresponds to situations where as many points as possible in the aperture emit rays that have no destructively interfering counterpart.

Taking a first-order approximation for small \( \Theta \) gives:

\[ \Theta = \Theta_0 + \left( \frac{\lambda}{2d} \right) k \]  \hspace{1cm} (6)
2.3. Expected Imaging Sensor Performance

Image sensor performance is evaluated by considering the spot size corresponding to an imaged distant point source. The angular resolution of the image sensor is estimated to be the angle change in incident light (in open air, outside the dielectric) required to displace the imaged spot by one diameter. This is evaluated as a function of both wavelength and angle of incident light.

2.3.1. Zone plate sensor

With incident light parallel to the optical axis and at the wavelength to which the zone plate is tuned, the zone plate should produce a spot size comparable to one wavelength of light (λ), as the f-number of the zone plate arrangement is approximately 0.5. The zone plate is 5 µm from the image plane, and the target wavelength λ in the dielectric is 325 nm. This gives an expected angular resolution under optimal conditions of about 0.065 radians within the dielectric (dielectric constant $n = 2$), corresponding to an expected angular resolution of about 0.13 radians in open air.

To evaluate spot size as a function of wavelength, consider the system shown in Figure 6a. Incident light is parallel to the optical axis, and the light of interest is in the first diffracted lobe’s maximum, so Equation 3 reduces to:

$$\Theta = \frac{\lambda}{d} \quad (7)$$

Designate $\Theta_{\lambda_0}$ the angle of diffraction at the edge of the lens for wavelength $\lambda_0$, the design wavelength at which an ideal zone plate would focus to a point. The focusing angle at different wavelengths can be estimated as:

$$\frac{\Theta}{\Theta_{\lambda_0}} = \frac{\lambda}{\lambda_0} \quad (8)$$

From Figure 6a, the spot radius $r_s$ can be found by considering similar triangles:

$$r_s = \left(\frac{r_0}{h}\right) (h_0 - h) \quad (9)$$

To the first order:

$$h = \frac{r_0}{\Theta} \quad (10)$$
Substituting into Equation 9 gives:

\[ r_s = r_0 \left( \frac{\lambda - \lambda_0}{\lambda_0} \right) \]  

(11)

The zone plate radius is 5 \( \mu \)m, and the target wavelength \( \lambda_0 \) in the dielectric is 325 nm. Under ideal conditions, the spot size is expected to be approximately 325 nm, giving a spot radius of approximately 160 nm. If the error induced by chromatic aberration is to be of no more than this magnitude, \( \lambda - \lambda_0 \) can be derived as:

\[ \lambda - \lambda_0 = 10.4 \text{nm} \]  

(12)

The open-air wavelength must be within about 20 nm, or about 3\%, of the tuned wavelength to preserve optimal resolution.

To evaluate spot size as a function of angle of incidence, consider the system shown in Figure 6b. Spot size is estimated by considering the deflection of light rays passing through the edge of the zone plate. From Equation 3, to the first order, the angle of deflection with respect to the original direction of propagation is independent of the angle of incidence \( \Theta_0 \) (changes in incident angle are precisely matched by changes in diffracted angle). As is shown in Figure 6b, this results in an effective change of the focal length of the zone plate, with rays from one edge having the focal length increased by \( \delta h \) and rays from the opposite edge having the focal length decreased by \( \delta h \). These changes in focal length have the effect of smearing the spot outwards radially (positive coma).

For small \( \Theta_0 \), the diameter of the smeared spot \( d_s \) can be estimated as:

\[ d_s = \delta h \tan \Theta_0 \]  

(13)

The values of \( \tan \Theta_0 \) and \( \delta h \) can be expressed as:

\[ \tan \Theta_0 = \left( \frac{r_0}{h} \right) \]  

(14)

\[ \delta h = r_0 \sin \Theta_0 \]  

(15)

To the first order, these reduce to:

\[ d_s = \left( \frac{r_0^2}{h} \right) \Theta_0 \]  

(16)

The zone plate radius is 5 \( \mu \)m, and the spacing between the zone plate and the image plane mask is 5 \( \mu \)m. Under ideal conditions, at the target wavelength (in the dielectric) of 325 nm, the spot diameter is expected to be approximately 325 nm. If the error induced by coma is to be of no more than this magnitude, \( \Theta_0 \) can be derived as:

\[ \Theta_0 = 0.065 \]  

(17)

The open-air angle must be within about 0.13 radians of the optical axis to preserve optimal resolution. This corresponds to a displacement of about 330 nm on the image plane, indicating that almost all parts of the image formed by the zone plate are expected to experience severe coma aberration.
2.3.2. Slit sensor

To evaluate spot size under optimal conditions and as a function of wavelength for a slit, consider the system shown in Figure 7a. Incident light is parallel to the optic axis, and the radius of the spot is estimated as being at the first minimum of the slit diffraction pattern. For spot sizes much larger than the slit size, spot radius is estimated to the first order to be:

\[ r_s = h\Theta \]  (18)

Substituting in Equation 6 gives:

\[ r_s = h \left[ \Theta_0 + \left( \frac{\lambda}{2d} \right) k \right] \]  (19)

As incident light is parallel to the optic axis, \( \Theta_0 \) is equal to zero. As the feature of interest is the first minimum, \( k = 2 \). This gives:

\[ r_s = h \left( \frac{\lambda}{d} \right) \]  (20)

Under design-targeted operating conditions, the wavelength \( \lambda \) is 325 nm in the inter-layer dielectric, the separation between the slit and the image plane mask is 5 \( \mu \)m, and the slit width is 1.2 \( \mu \)m. This gives a spot size of:

\[ r_s = 1350\text{nm} \]  (21)

This corresponds to an open-air angular resolution \( \Theta_{\text{slit}} \) of:

\[ \Theta_{\text{slit}} = n \left( \frac{2r_s}{h} \right) \]  (22)

\[ \Theta_{\text{slit}} = 1.1 \text{ rad} \]  (23)

Spot size is expected to decrease as wavelength decreases, allowing improved resolution for short wavelengths. Unlike the zone plate, the slit can form images using monochromatic illumination of any wavelength detectable by the underlying photosensor.
<table>
<thead>
<tr>
<th></th>
<th>Zone Plate</th>
<th>Slit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Resolution (650 nm)</td>
<td>0.13 rad</td>
<td>1.1 rad</td>
</tr>
<tr>
<td>Tolerable Wavelength Deviation</td>
<td>3% (20 nm)</td>
<td>30% (200 nm)</td>
</tr>
<tr>
<td>Tolerable Angle Deviation</td>
<td>0.13 rad</td>
<td>any</td>
</tr>
</tbody>
</table>

Table 1. Expected imaging behavior for zone plates and slits.

In order for an image to be negligibly affected by chromatic aberration, variation in spot size corresponding to different spectral components of the incident light must be below a certain threshold corresponding to the definition chosen for “negligible effect”. For zone plate imaging, variation up to 100% of the spot size was assumed to be acceptable; however, such a large variation with the slit imager would remove its ability to produce images. If 30% variation in the spot size is acceptable, then from Equation 20, wavelengths in the incident light can vary by ±30% from the nominal illumination wavelength. For the design wavelength of 650 nm, this corresponds to about ±200 nm.

To evaluate spot size as a function of the angle of incidence $\Theta_0$ of incident light for a slit, consider the system shown in Figure 7b. From Equation 6, the diffraction pattern minima corresponding to the edge of the spot can be found at $k = \pm 2$. The difference between these angles, corresponding to the sensor’s angular resolution for spot sizes much larger than the slit size, is:

$$\Theta_s = 2 \left( \frac{\lambda}{d} \right)$$

(24)

As this is independent of $\Theta_0$, the angular resolution of the sensor is not affected by angle of incidence of incoming light to the first order.

The spot size on the image plane is affected as shown in Figure 7b. Spot size is estimated as:

$$d_s = h \tan(\Theta_0 + $\Theta$) - h \tan(\Theta_0 - $\Theta$)$$

(25)

To the first order, this is:

$$d_s = 2h$\Theta$

(26)

As this is independent of $\Theta_0$, spot size is not substantially affected by angle of incidence, for small $\Theta_0$.

2.3.3. Summary of expected performance

Expected behavior of zone plates and slits for imaging is summarized in Table 1. Zone plates achieve high angular resolution but must be customized for each angle of incidence and operated at their intended target wavelength. Slits achieve low angular resolution, but are relatively insensitive to wavelength and are almost completely insensitive to angle of incidence.

2.4. Expected Spectral Sensor Performance

Spectral sensors are assumed to operate in a scenario where illumination is parallel to the optical axis of the system. The spectral resolution is estimated to be the wavelength change in incident light (in open air, outside the dielectric) required to displace the diffraction pattern fringe being tracked by the sensor by one wavelength. This is evaluated as a function of wavelength.
2.4.1. Zone plate sensor

As was described in Section 2.3.1, changes in the wavelength of incident light alter the size of the spot imaged by a zone plate, by changing the effective focal length of the system. This is illustrated in Figure 6a. Measuring the size of the spot gives information about the wavelength of incident light. From Equation 11, the relation is as follows, where \( r_0 \) is the radius of the zone plate, \( \lambda_0 \) is the target wavelength of the zone plate in the dielectric, and \( \lambda \) is the incident wavelength:

\[
r_s = r_0 \left( \frac{\lambda - \lambda_0}{\lambda_0} \right) \tag{27}
\]

Taking the difference of the spot radii corresponding to two wavelengths gives:

\[
r_a - r_b = (\lambda_a - \lambda_b) \left( \frac{r_0}{\lambda_0} \right) \tag{28}
\]

If the spot size is to change by \( \lambda_a \), this gives:

\[
\lambda_a - \lambda_b = \left( \frac{\lambda_0}{r_0} \right) \lambda_a \tag{29}
\]

Substituting in the radius of the fabricated zone plate and its target wavelength in the inter-layer dielectric gives:

\[
\lambda_a - \lambda_b = 0.065\lambda_a \tag{30}
\]

This indicates that the zone plate is estimated to distinguish wavelengths that differ by about 6.5%, or about 40 nm in open air at the target open-air wavelength of 650 nm.

2.4.2. Slit sensor

The diffraction pattern produced by a slit is shown in Figure 3b. The position of the diffracted lobes depends on the illumination wavelength. For purposes of estimating wavelength sensitivity, the position of the maximum of the first lobe is designated the feature being measured to infer wavelength. The relation between lobe position and wavelength is given by Equation 6 for the case where \( k = 3 \) and angle of incidence \( \Theta_0 = 0 \):

\[
\Theta = \left( \frac{3}{2} \right) \left( \frac{\lambda}{d} \right) \tag{31}
\]

Substituting Equation 18 and taking the difference between the displacements corresponding to two wavelengths gives:

\[
r_a - r_b = (\lambda_a - \lambda_b) \left( \frac{3}{2} \right) \left( \frac{h}{d} \right) \tag{32}
\]

If the spot size is to change by \( \lambda_a \), this becomes:

\[
\lambda_a - \lambda_b = \lambda_a \left( \frac{2}{3} \right) \left( \frac{d}{h} \right) \tag{33}
\]

Substituting in the size of the narrower slit and the distance between the slit and the image plane mask gives:

\[
\lambda_a - \lambda_b = 0.080\lambda_a \tag{34}
\]

This indicates that the slit is estimated to distinguish wavelengths that differ by about 8.0%, or about 50 nm in open air at the target open-air wavelength of 650 nm.
<table>
<thead>
<tr>
<th></th>
<th>Zone Plate</th>
<th>Slit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Resolution</td>
<td>6.5% (40 nm)</td>
<td>8.0% (50 nm)</td>
</tr>
</tbody>
</table>

Table 2. Expected spectral discrimination behavior for zone plates and slits.

2.4.3. Summary of expected performance

Expected behavior of zone plates and slits for spectral discrimination is summarized in Table 2. Illumination must be aligned with the optical axis of the sensor, but both zone plates and slits are estimated to have reasonably high spectral resolution when used with monochromatic illumination. In principle, the same resolution is achievable with polychromatic illumination by decomposing measured input into a linear combination of the diffraction patterns corresponding to a series of reference wavelengths. In practice, this is expected to be limited by noise issues.

3. SIMULATED BEHAVIOR

3.1. Simulation Methodology

Simulations of expected sensor behavior were performed using Matlab. Simplifying assumptions made were as follows:

- Illumination consists of an ideal plane wave, corresponding to a perfectly coherent monochromatic source at infinite distance.
- Thickness of the optical element is neglected. No phase shifting or sidewall reflections occur as a result of propagating through it.
- All light striking the open parts of the mask is assumed to contribute uniformly to the detected signal, independent of angle of incidence, photosensor sensitivity variations, and thickness of the mask.
- Illumination is bright enough to consider measured values as continuous. Noise due to photon count effects is zero.

Point spread functions on the image plane at the level of the mask were simulated as shown in Figure 8. A plane wave incident at the top of the optical element was represented as an array of complex values with constant magnitude and varying phase. The plane wave was masked by the optical element. Huygen’s principle was applied to construct the interference pattern at the altitude of the mask. This was implemented by convolving the masked version of the plane wave by a template representing the intensity and phase of the light contributions from a single point at the altitude of the optical element. Examples of the resulting point spread functions can be found in Figure 9. Optical element masks reflect the implemented configurations described in Section 2.
3.2. Simulated Imaging Sensor Performance

Simulation of imaging sensor performance was accomplished by computing the point spread function of the imager as a function of open-air angle of incidence at a fixed wavelength. The resulting image was converted to a binary-valued stencil thresholded to discard low-intensity areas. The centroid of the above-threshold region was taken to be the centroid of the imaged point, and the maximum displacement of above-threshold pixels from the centroid was taken to be the radius of the imaged spot.

Figure 10a) shows a plot of simulated displacement vs. open-air angle of incidence for a Fresnel zone plate and for a 1.2 µm wide slit. The zone plate is tuned to and tested at an open-air wavelength of 800 nm, and the slit is tested at a wavelength of 650 nm. In both cases, the spot size is approximately constant. For the zone plate, the spot diameter is 400±40 nm, and for the slit, the spot width is 1680±40 nm. If the discernable angular resolution is taken to be the change in angle that causes a spot displacement of one diameter, then the zone plate imager produces an angular resolution of approximately 0.3 rad (±0.15 rad position uncertainty), and the wide slit imager has difficulty imaging at all at 650 nm (1.4 rad resolution). Expressing the slit’s image as a linear combination of slit point spread functions with centroids displaced by one wavelength (325 nm in the dielectric) yields a slit imager resolution of approximately 0.3 rad, subject to noise concerns. This technique does not improve zone plate resolution, as the spot size is already comparable to one wavelength (no reconstruction required). It is also significant to note that the strong coma aberration predicted in Section 2.3.1 was not
3.3. Simulated Spectral Sensor Performance

Simulation of spectral sensor performance was accomplished by computing the point spread function of the sensor as a function of open-air wavelength with incident light aligned with the optical axis. The resulting image was converted to a binary-valued stencil thresholded to discard low-intensity areas. The centroid of the above-threshold region was taken to be the centroid of the imaged point, and the maximum displacement of above-threshold pixels from the centroid was taken to be the radius of the imaged spot. This radius was tracked as a function of wavelength. Changes in radius of approximately 300 nm can be discriminated; this is used to find the corresponding spectral resolution of the sensors. For slits, this corresponds to the central lobe of the slit diffraction pattern. Greater spectral resolution could be obtained by tracking secondary lobes.

Figure 10b) shows a plot of simulated spot radius vs. open-air wavelength for a 1.2 µm wide slit and for a 0.6 µm narrow slit. Incident light is aligned with the optical axis. If the discernable spot radius change is taken to be 300 nm, the spectral resolutions of the wide and narrow slit sensors are approximately 250 nm and 80 nm, respectively. Zone plate spectral response was not simulated.

4. CONCLUSIONS

An implementation of on-die optics fabricated using a conventional 0.18 µm bulk CMOS process is described. The angular resolutions of the fabricated Fresnel zone plate and wide slit image sensors are estimated to be 0.13 and 1.1 radian, and are simulated to be 0.3 and 1.4 radian, respectively. Improvement of the slit sensor’s angular resolution is expected to be possible to a limited degree through numerical post-processing. The spectral resolutions of the fabricated Fresnel zone plate and narrow slit image sensors are estimated to be 40 nm and 50 nm, respectively, and the simulated spectral resolutions of wide and narrow slits are 250 nm and 80 nm, respectively. Zone plate spectral resolution was not simulated.

REFERENCES