Detecting the direction of ambient light using an array of photodiodes

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Detecting the direction of ambient light using an array of photodiodes

1 Abstract

So as to gain context, mobile devices, e.g., phones, tablets, laptops, etc., capture information about their surroundings, including sounds, lights, temperature, etc. An important piece of information is the direction of nearby light sources. Currently available ambient light sensors provide illuminance information so that the display can adjust its brightness accordingly. However, there is no directional information provided.

This disclosure describes techniques that use a planar array of ambient light sensors with asymmetric masks to determine the angle of incident light.

2 Keywords

Ambient light; direction of light; light angle; photodiode; masked aperture; light sensor

3 Background

So as to gain context, mobile devices, e.g., phones, tablets, laptops, etc., capture information about their surroundings, including sounds, lights, temperature, etc. An important piece of information is the direction of nearby light sources. Currently available ambient light sensors provide illuminance information so that the display can adjust its brightness accordingly. However, there is no directional information provided.

4 Description

The techniques of this disclosure utilize an array of light sensors, e.g., photodiodes, with apertures designed to sense the direction of light sources. Typical aperture design for light sensors is symmetrical in order to collect as much light as possible. However, the techniques herein intentionally cover up a portion of the aperture such that the field-of-view for a photodiode shifts in a preferred direction, e.g., the top-left direction. A 2x2 photodiode array is installed in a device, e.g., phone, tablet, laptop, such that each constituent diode has a preferred light-sensing direction, e.g., top-left, top-right, bottom-left, bottom-right. The ratios of the photodiode outputs indicate the direction of the incident light.

4.1 Shadow-based model

4.1.1 One sensor. One dimension. No mask

Assume that the sensor has a uniform sensitivity across the length. Normalized light intensity ($I_n$) has a field-of-view function close to cosine (Fig. 2). Line integral gives a total amount of light intensity received by the sensor. Note that from received light intensity, due to the symmetry in the field-of-view, angle polarity cannot be recovered.
Figure 1: One-dimensional model of the sensor and incident light. Incidental angle is marked as $\theta$. Sensor has a length of $L$.

Figure 2: Field-of-view of a typical sensor. X-axis is incidental angle (or illuminance angle, $\theta$) and Y-axis is normalized light intensity ($f(\theta)$).

\[ I_n = f(\theta) \approx \cos \theta \]  
\[ I = \int_{-L/2}^{L/2} f(\theta) \, dx = L f(\theta) \]
4.1.2 Two sensors. One dimension. Asymmetric mask

![Diagram of two sensors with an asymmetric mask]

Figure 3: Side-view model of the two sensors (sensor 1, 2) and an asymmetric mask (aperture 1, 2). Sensors have a length of $L$ and are spaced by $S$ (edge-to-edge). The mask has a vertical gap of $H$. One side of the aperture has a margin of $W$ from the sensor edge while the other side of the aperture is aligned. Top figure shows light coming from aperture 1 to sensor 1. Bottom figure shows light coming from aperture 2 to sensor 1.

Fig. 3 shows a side-view model of the two sensors with an asymmetric mask. Note that sensor 1 can receive light from both aperture 1 and aperture 2. We will note light intensity received by sensor $i$ from aperture $j$ as $I_{ij}$.

We make a couple of assumptions here. Sensors have a uniform sensitivity across their lengths. All light intensities received by sensor $i$ are superposed ($I_i = \Sigma_j I_{ij}$). Sensor thickness is not considered. Mask thickness is not considered. Masks completely block incidental light. There is no change in medium (i.e. no refraction).

Aperture 1 creates shades on sensor 1 (boundary angles are marked as $\theta_1$, $\theta_2$, $\theta_3$) and aperture 2 creates shades on sensor 1 (boundary angles are marked as $\theta_4$, $\theta_5$, $\theta_6$, $\theta_7$).

\[
\begin{align*}
\theta_1 &= \tan^{-1}\left(\frac{W}{H}\right), \quad \theta_2 = \tan^{-1}\left(\frac{L+W}{H}\right), \quad \theta_3 = \tan^{-1}\left(\frac{L}{H}\right) \\
\theta_4 &= \tan^{-1}\left(\frac{S}{H}\right), \quad \theta_5 = \tan^{-1}\left(\frac{L+S}{H}\right), \quad \theta_6 = \tan^{-1}\left(\frac{L+S+W}{H}\right), \quad \theta_7 = \tan^{-1}\left(\frac{2L+S+W}{H}\right)
\end{align*}
\]

\[
I_{11} = \begin{cases} 
0 & \text{for } \theta > \theta_3 \\
(L - H \tan|\theta|)f(\theta) & \text{for } 0 < \theta \leq \theta_3 \\
Lf(\theta) & \text{for } -\theta_1 < \theta \leq 0 \\
(W + L - H \tan|\theta|)f(\theta) & \text{for } -\theta_2 < \theta \leq -\theta_1 \\
0 & \text{for } \theta \leq -\theta_2
\end{cases}
\]

\[
I_{12} = \begin{cases} 
0 & \text{for } \theta > \theta_7 \\
(2L+S+W-H \tan|\theta|)f(\theta) & \text{for } \theta_6 < \theta \leq \theta_7 \\
Lf(\theta) & \text{for } \theta_5 < \theta \leq \theta_6 \\
(H \tan|\theta| - S)f(\theta) & \text{for } \theta_4 < \theta \leq \theta_5 \\
0 & \text{for } \theta \leq \theta_4
\end{cases}
\]
Since sensor 2 and aperture 2 are symmetric to sensor 1 and aperture 1, \( I_{22} \) and \( I_{21} \) have the same equation as \( I_{11} \) and \( I_{12} \) respectively with flipped \( \theta \) intervals.

\[
I_{22} = \begin{cases} 
0 & \text{for } \theta < -\theta_3 \\
(L - H \tan |\theta|) f(\theta) & \text{for } -\theta_3 \leq \theta < 0 \\
Lf(\theta) & \text{for } 0 \leq \theta < \theta_1 \\
(W + L - H \tan |\theta|) f(\theta) & \text{for } \theta_1 \leq \theta < \theta_2 \\
0 & \text{for } \theta \geq \theta_2 
\end{cases} \tag{7}
\]

\[
I_{21} = \begin{cases} 
0 & \text{for } \theta < -\theta_7 \\
(2L + S + W - H \tan |\theta|) f(\theta) & \text{for } -\theta_7 \leq \theta < -\theta_6 \\
Lf(\theta) & \text{for } -\theta_6 \leq \theta < -\theta_5 \\
(H \tan |\theta| - S) f(\theta) & \text{for } -\theta_5 \leq \theta < -\theta_4 \\
0 & \text{for } \theta \geq -\theta_4 
\end{cases} \tag{8}
\]

Polarity and absolute value of the incident angle can be known by taking subtraction and ratio of \( I_1 \) and \( I_2 \). For simplicity, we ignore \( I_{12} \) and \( I_{21} \). We also assume \( W = L \) to make \( \theta_1 = \theta_3 \). If \( I_1 \) is larger than \( I_2 \), \( \theta \) is negative. If \( I_1 \) is smaller than \( I_2 \), \( \theta \) is positive. Absolute value of \( \theta \) can be known by taking a ratio \( I_{ratio} \) like below:

\[
I_{ratio} = \begin{cases} 
I_2/I_1 & \text{for } I_1 > I_2 \\
I_1/I_2 & \text{for } I_1 < I_2 
\end{cases} \tag{9}
\]

Since the sensors’ angle responses get cancelled by taking a ratio, \( I_{ratio} \) only depends on \( L \) and \( H \), and \( |\theta| \) can get recovered with an inverse tangent function.

\[
|\theta| = \frac{L}{H} \tan^{-1} (1 - I_{ratio}) \tag{10}
\]
Figure 4: Side-view model of the two sensors (sensor 1, 2) and an asymmetric mask (aperture 1, 2) with misalignment. For simplicity, crosstalk between aperture $i$ and sensor $j$ ($i \neq j$) is ignored. Aperture 1 is misaligned by $\Delta L_1$ and aperture 2 is misaligned by $\Delta L_2$.

Fig. 4 shows a case when there are misalignment between masks and sensor areas. Presence of misalignment make peaks of the received light deviate from center points ($\theta = 0$).

\[
\theta_{11} = \tan^{-1}\left(\frac{W + \Delta L_1}{H}\right), \quad \theta_{12} = \tan^{-1}\left(\frac{L + W + \Delta L_1}{H}\right)
\]

\[
\theta_{13} = \tan^{-1}\left(\frac{L - \Delta L_1}{H}\right), \quad \theta_{14} = \tan^{-1}\left(\frac{\Delta L}{H}\right)
\]

\[
I_1 = \begin{cases} 
0 & \text{for } \theta > \theta_{13} \\
(L - \Delta L_1 - H \tan \theta)f(\theta) & \text{for } -\theta_{14} < \theta \leq \theta_{13} \\
f(\theta) & \text{for } -\theta_{11} < \theta \leq -\theta_{14} \\
(W + \Delta L_1 + L - H \tan \theta)f(\theta) & \text{for } -\theta_{12} < \theta \leq -\theta_{11} \\
0 & \text{for } \theta \leq -\theta_{12}
\end{cases}
\]

\[
\theta_{21} = \tan^{-1}\left(\frac{W - \Delta L_2}{H}\right), \quad \theta_{22} = \tan^{-1}\left(\frac{L + W - \Delta L_2}{H}\right)
\]

\[
\theta_{23} = \tan^{-1}\left(\frac{L + \Delta L_2}{H}\right), \quad \theta_{24} = \tan^{-1}\left(\frac{\Delta L_2}{H}\right)
\]

\[
I_2 = \begin{cases} 
0 & \text{for } \theta < -\theta_{23} \\
(L - \Delta L_2 + H \tan \theta)f(\theta) & \text{for } -\theta_{23} \leq \theta < -\theta_{24} \\
f(\theta) & \text{for } \theta_{24} \leq \theta < -\theta_{21} \\
(W + \Delta L_2 + L - H \tan \theta)f(\theta) & \text{for } -\theta_{21} \leq \theta < -\theta_{22} \\
0 & \text{for } \theta > -\theta_{22}
\end{cases}
\]
4.1.3 One sensor. Two dimensions. Asymmetric mask

Another interesting case is having one two-dimensional sensor. As shown in Fig. 5, the sensor is located in the grey-colored area with dimensions $L_x$ and $L_y$ along x-axis and y-axis respectively. The mask is installed with a vertical gap of $H$. Note that the mask has asymmetry; its north edge and east edge are aligned with sensors while its south edge and west edge have margins from sensors ($W_x$ and $W_y$). Fig. 6 shows a top view.

Figure 5: Three-dimensional view of one two-dimensional sensor with an asymmetric aperture. Sensor area is colored with grey.

Figure 6: Top view of Fig. 5.

Figure 7: Coordinate for marking incident angles: spherical coordinate (left) and custom coordinate (right). Projected rays are marked with solid red lines.

A conventional way of quantifying an incident light ray is using the spherical coordinate as shown in Fig. 7 (left). Angle between z-axis and the ray is marked ($\theta$) and angle between x-axis and the projected ray (to x-y plane) is marked ($\phi$). The original ray can be recovered by overlapping a cone given by $\theta$ and a plane given by $\phi$.

We take a similar but different approach as shown in Fig. 7 (right). We project the ray to y-z plane and mark the angle between z-axis and the projected ray ($\theta_y$). We also project the ray to x-z plane and mark the angle between z-axis and the projected ray ($\theta_x$). The original ray can be recovered by overlapping a plane given by $\theta_y$ and another plane given by $\theta_x$.

Fig. 8 shows side views of the setup either along x-axis (top) or along y-axis (bottom). If the light ray is blocked in either direction, the sensor cannot pick it up. Because this is a logical AND condition, a light ray $I(\theta_x, \theta_y)$ is a multiplication of $I_x(\theta_x)$ and $I_y(\theta_y)$ where $I_x(\theta_x)$ and $I_y(\theta_y)$ are listed below.

$$I(\theta_x, \theta_y) = I_x(\theta_x)I_y(\theta_y)$$ (17)
\[ \theta_{x1} = \tan^{-1} \left( \frac{W_x}{H} \right), \quad \theta_{x2} = \tan^{-1} \left( \frac{L_x + W_x}{H} \right), \quad \theta_{x3} = \tan^{-1} \left( \frac{L_x}{H} \right) \] (18)

\[ \theta_{y1} = \tan^{-1} \left( \frac{W_y}{H} \right), \quad \theta_{y2} = \tan^{-1} \left( \frac{L_y + W_y}{H} \right), \quad \theta_{y3} = \tan^{-1} \left( \frac{L_y}{H} \right) \] (19)

\[ I_x = \begin{cases} 0 & \text{for } \theta_x > \theta_{x3} \\ (L_x - H \tan |\theta_x|)f(\theta_x) & \text{for } 0 < \theta_x \leq \theta_{x3} \\ L_x f(\theta_x) & \text{for } -\theta_{x1} < \theta_x \leq 0 \\ (W_x + L_x - H \tan |\theta_x|)f(\theta_x) & \text{for } -\theta_{x2} < \theta_x \leq -\theta_{x1} \\ 0 & \text{for } \theta_x \leq -\theta_{x2} \end{cases} \] (20)

\[ I_y = \begin{cases} 0 & \text{for } \theta_y > \theta_{y3} \\ (L_y - H \tan |\theta_y|)f(\theta_y) & \text{for } 0 < \theta_y \leq \theta_{y3} \\ L_y f(\theta_y) & \text{for } -\theta_{y1} < \theta_y \leq 0 \\ (W_y + L_y - H \tan |\theta_y|)f(\theta_y) & \text{for } -\theta_{y2} < \theta_y \leq -\theta_{y1} \\ 0 & \text{for } \theta_y \leq -\theta_{y2} \end{cases} \] (21)

Figure 8: Side views of the one two-dimensional sensor with the asymmetric mask along x-axis (top) and along y-axis (bottom). The mask has a vertical gap of $H$. 
4.1.4 Four sensors. Two dimensions. Asymmetric mask

With so-far discussed methods such as superposition and decomposition of incident light, four two-dimensional sensors with an asymmetric mask shown in Fig. 9 can be analyzed with a bit more complexity. Sensor areas are colored with grey. Along x-/y-axis, sensor dimensions are marked with $L$, aperture margin is marked with $W$, and edge-to-edge spacing are marked with $S$. The vertical gap between the sensors and the mask is $H$. Note the alignment of the sensors and the apertures. Fig. 10 shows a top view of the setup.

![Diagram of four two-dimensional sensors with asymmetric mask](image)

Figure 9: Three-dimensional view of four two-dimensional sensors with an asymmetric mask. Sensors are numbered starting from 1 (bottom left) to 4 (top right).

As before, we assume that light intensities received by sensor $i$ come from aperture $j$ superpose. Since we decompose a ray into two-dimensional angles ($I_{xij}$, $I_{yij}$), AND condition gets applied first before superposition.

$$I_i = \sum_{j=1}^{4} I_{xij} I_{yij} \quad (22)$$

Here we walk through derivations of $I_{xij}$ in detail. Fig. 11 shows a side-view model along x-axis. Shades are made with boundary angles ($\theta_{x1}$, ..., $\theta_{x7}$). Due to symmetry, we only need to consider four cases: from an odd numbered aperture to an odd numbered sensor, from an even numbered aperture to an odd numbered sensor, from an even numbered aperture to an even numbered sensor, and from an even numbered aperture to an odd numbered sensor.

$$\theta_{x1} = \tan^{-1} \left( \frac{W_x}{H} \right), \quad \theta_{x2} = \tan^{-1} \left( \frac{L_x + W_x}{H} \right), \quad \theta_{x3} = \tan^{-1} \left( \frac{L_x}{H} \right)$$

$$\theta_{x4} = \tan^{-1} \left( \frac{S_x}{H} \right), \quad \theta_{x5} = \tan^{-1} \left( \frac{L_x + S_x}{H} \right)$$

$$\theta_{x6} = \tan^{-1} \left( \frac{L_x + S_x + W_x}{H} \right), \quad \theta_{x7} = \tan^{-1} \left( \frac{2L_x + S_x + W_x}{H} \right) \quad (23) \quad (24) \quad (25)$$

$$I_{x11} = I_{x31} = I_{x33} = I_{x33} = \begin{cases} 0 & \text{for } \theta_x > \theta_{x3} \\ (L_x - H \tan |\theta_x|) f(\theta_x) & \text{for } 0 < \theta_x \leq \theta_{x3} \\ L_x f(\theta_x) & \text{for } -\theta_{x1} < \theta_x \leq 0 \\ (W_x + L_x - H \tan |\theta_x|) f(\theta_x) & \text{for } -\theta_{x2} < \theta_x \leq -\theta_{x1} \\ 0 & \text{for } \theta_x \leq -\theta_{x2} \end{cases} \quad (26)$$
\[ I_{x12} = I_{x14} = I_{x32} = I_{x34} = \begin{cases} 0 & \text{for } \theta_x > \theta_x 7 \\ (2L_x + S_x + W_x - H \tan |\theta_x|)f(\theta_x) & \text{for } \theta_x 6 < \theta_x \leq \theta_x 7 \\ L_x f(\theta) & \text{for } \theta_x 5 < \theta_x \leq \theta_x 6 \\ (H \tan |\theta_x| - S_x)f(\theta_x) & \text{for } \theta_x 4 < \theta_x \leq \theta_x 5 \\ 0 & \text{for } \theta_x \leq \theta_x 4 \end{cases} \] (27)

\[ I_{x22} = I_{x24} = I_{x42} = I_{x44} = \begin{cases} 0 & \text{for } \theta_x > -\theta_x 3 \\ (L_x - H \tan |\theta_x|)f(\theta_x) & \text{for } -\theta_x 3 \leq \theta_x < 0 \\ L_x f(\theta_x) & \text{for } 0 \leq \theta_x \leq \theta_x 1 \\ (W_x + L_x - H \tan |\theta_x|)f(\theta_x) & \text{for } \theta_x 1 \leq \theta_x < \theta_x 2 \\ 0 & \text{for } \theta_x \geq \theta_x 2 \end{cases} \] (28)

\[ I_{x21} = I_{x23} = I_{x41} = I_{x43} = \begin{cases} 0 & \text{for } \theta_x > -\theta_x 7 \\ (2L_x + S_x + W_x - H \tan |\theta_x|)f(\theta_x) & \text{for } -\theta_x 7 \leq \theta_x < -\theta_x 6 \\ L_x f(\theta) & \text{for } -\theta_x 6 \leq \theta_x < -\theta_x 5 \\ (H \tan |\theta_x| - S_x)f(\theta_x) & \text{for } -\theta_x 5 \leq \theta_x < -\theta_x 4 \\ 0 & \text{for } \theta_x \geq -\theta_x 4 \end{cases} \] (29)

Fig. 10: Top view of Fig. 9.

Fig. 12 shows a side-view model along y-axis. Due to the symmetry between x-axis and y-axis, the y-axis model is the same with the x-axis model except sub-indices. Shades are made with boundary angles \((\theta_y 1, \ldots, \theta_y 7)\).
Figure 11: Side-view model of Fig. 9 along x-axis. Top figure shows light coming from aperture 1 to sensor 1. Bottom figure shows light coming from aperture 2 to sensor 1.

\[
\theta_{y1} = \tan^{-1}\left(\frac{W_y}{H}\right), \quad \theta_{y2} = \tan^{-1}\left(\frac{L_y + W_y}{H}\right), \quad \theta_{y3} = \tan^{-1}\left(\frac{L_y}{H}\right) \quad (30)
\]

\[
\theta_{y4} = \tan^{-1}\left(\frac{S_y}{H}\right), \quad \theta_{y5} = \tan^{-1}\left(\frac{L_y + S_y}{H}\right) \quad (31)
\]

\[
\theta_{y6} = \tan^{-1}\left(\frac{L_y + S_y + W_y}{H}\right), \quad \theta_{y7} = \tan^{-1}\left(\frac{2L_y + S_y + W_y}{H}\right) \quad (32)
\]

\[
I_{y11} = I_{y12} = I_{y21} = I_{y22} = \begin{cases} 
0 & \text{for } \theta_y > \theta_{y3} \\
(L_y - H \tan |\theta_y|) f(\theta_y) & \text{for } 0 < \theta_y \leq \theta_{y3} \\
L_y f(\theta_y) & \text{for } -\theta_{y2} < \theta_y \leq 0 \\
(W_y + L_y - H \tan |\theta_y|) f(\theta_y) & \text{for } -\theta_{y2} < \theta_y \leq -\theta_{y1} \\
0 & \text{for } \theta_y \leq -\theta_{y2}
\end{cases} \quad (33)
\]

Figure 12: Side-view model of Fig. 9 along y-axis. Top figure shows light coming from aperture 1 to sensor 1. Bottom figure shows light coming from aperture 3 to sensor 1.
\[ I_{y13} = I_{y14} = I_{y23} = I_{y24} = \begin{cases} 
0 & \text{for } \theta_y > \theta_y^7 \\
(2L_y + S_y + W_y - H \tan|\theta_y|) f(\theta_y) & \text{for } \theta_y^6 < \theta_y \leq \theta_y^7 \\
L_y f(\theta) & \text{for } \theta_y^5 < \theta_y \leq \theta_y^6 \\
(H \tan|\theta_y| - S_y) f(\theta_y) & \text{for } \theta_y^4 < \theta_y \leq \theta_y^5 \\
0 & \text{for } \theta_y \leq \theta_y^4 
\end{cases} \quad (34) \]

\[ I_{y33} = I_{y34} = I_{y43} = I_{y44} = \begin{cases} 
0 & \text{for } \theta_y < -\theta_y^3 \\
(L_y - H \tan|\theta_y|) f(\theta_y) & \text{for } -\theta_y^3 \leq \theta_y < 0 \\
L_y f(\theta_y) & \text{for } 0 \leq \theta_y < \theta_y^1 \\
(W_y + L_y - H \tan|\theta_y|) f(\theta_y) & \text{for } \theta_y^1 \leq \theta_y < \theta_y^2 \\
0 & \text{for } \theta_y \geq \theta_y^2 
\end{cases} \quad (35) \]

\[ I_{y31} = I_{y32} = I_{y41} = I_{y42} = \begin{cases} 
0 & \text{for } \theta_y < -\theta_y^7 \\
(2L_y + S_y + W_y - H \tan|\theta_y|) f(\theta_y) & \text{for } -\theta_y^7 \leq \theta_y < -\theta_y^6 \\
L_y f(\theta) & \text{for } -\theta_y^6 \leq \theta_y < -\theta_y^5 \\
(H \tan|\theta_y| - S_y) f(\theta_y) & \text{for } -\theta_y^5 \leq \theta_y < -\theta_y^4 \\
0 & \text{for } \theta_y \geq -\theta_y^4 
\end{cases} \quad (36) \]
4.2 Simulation results

Two sets of (air gap, aperture margin) are tested based on real-life assembly of typical ambient light sensor arrays.

4.2.1 Two sensors. One dimension. Asymmetric mask

Fig. 13 shows light intensities received by sensor 1 and sensor 2 (schematic is shown in Fig. 3). For sensor 1, when the incident angle is $-\theta_1 = -45\,\text{deg} < \theta < 0\,\text{deg}$, there is no shadow. If the incident angle is $\theta < -\theta_1 = -45\,\text{deg}$ or $\theta > 0\,\text{deg}$, received light intensity decreases due to shadows created by masks. For a deep positive incident light $\theta_4 = 65\,\text{deg} < \theta < \theta_7 = 74\,\text{deg}$, light through aperture 2 hits sensor 1. The received light intensity of sensor 2 is symmetric to the received light intensity of sensor 1.

![Figure 13: Received light intensity of sensor 1 ($I_1$) and sensor 2 ($I_2$). Lux value is not normalized. Sensor length is $L = 0.39\,\text{mm}$. Air gap is $H = 1.62\,\text{mm}$. Aperture margin is $W = 1.61\,\text{mm}$. Sensor edge-to-edge spacing is $S = 3.42\,\text{mm}$.](image)

Fig. 14 shows a case of a narrower air gap and a smaller aperture margin. The narrower gap and the smaller aperture margin increases range of incident angles to be detected. The smaller aperture reduces the effect of light coming from a non-aligned aperture.

![Figure 14: Received light intensity of sensor 1 ($I_1$) and sensor 2 ($I_2$). Lux value is not normalized. Sensor length is $L = 0.39\,\text{mm}$. Air gap is $H = 0.49\,\text{mm}$. Aperture margin is $W = 0.61\,\text{mm}$. Sensor edge-to-edge spacing is $S = 3.42\,\text{mm}$.](image)

One way of getting polarity of the incident angle is taking a subtraction of $I_1$ and $I_2$ (with ignoring the effect of light coming from a non-aligned aperture). Absolute value of the angle can be derived from ratio of $I_1$ and $I_2$. 

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Next plots show the effect of controlling the air gap $H$ while maintaining $W = L$ and a fixed $S$. Note that the angle range $\theta_3$ increases with a smaller $H$ but with a larger nonlinearity.

![Graph](image1)

(a) $I_1$ and $I_2$

(b) $I_{ratio}$

Figure 15: Received light intensity of sensor 1 and sensor 2. Lux value is not normalized. Sensor length is $L = 0.39$mm. Air gap is $H = 0.1$mm. Aperture margin is $W = 0.39$mm. Sensor edge-to-edge spacing is $S = 3.42$mm.

![Graph](image2)

(a) $I_1$ and $I_2$

(b) $I_{ratio}$

Figure 16: Received light intensity of sensor 1 and sensor 2. Lux value is not normalized. Sensor length is $L = 0.39$mm. Air gap is $H = 0.2$mm. Aperture margin is $W = 0.39$mm. Sensor edge-to-edge spacing is $S = 3.42$mm.
Figure 17: Received light intensity of sensor 1 and sensor 2. Lux value is not normalized. Sensor length is $L = 0.39$mm. Air gap is $H = 0.4$mm. Aperture margin is $W = 0.39$mm. Sensor edge-to-edge spacing is $S = 3.42$mm.

Figure 18: Received light intensity of sensor 1 and sensor 2. Lux value is not normalized. Sensor length is $L = 0.39$mm. Air gap is $H = 0.8$mm. Aperture margin is $W = 0.39$mm. Sensor edge-to-edge spacing is $S = 3.42$mm.
4.2.2 One sensor. Two dimensions. Asymmetric mask

Fig. 19 shows received light intensity of a two-dimensional sensor with a larger air gap and a wider aperture margin, and Fig. 20 shows a case of a smaller air gap and a narrower aperture margin. Note the directionality, range, and sensitivity. Schematic is shown in Fig. 5 and Fig. 8.

![Figure 19](image1.png)

Figure 19: Received light intensity of a two-dimensional sensor. Lux value is not normalized. Sensor lengths are $L_x = 0.39\text{mm}$ and $L_y = 0.49\text{mm}$. Air gap is $H = 1.62\text{mm}$. Aperture margins are $W_x = 1.61\text{mm}$ and $W_y = 1.51\text{mm}$. Sensor edge-to-edge spacing are $S_x = 3.42\text{mm}$ and $S_y = 2.51\text{mm}$.

![Figure 20](image2.png)

Figure 20: Received light intensity of a two-dimensional sensor. Lux value is not normalized. Sensor lengths are $L_x = 0.39\text{mm}$ and $L_y = 0.49\text{mm}$. Air gap is $H = 0.49\text{mm}$. Aperture margins are $W_x = 0.61\text{mm}$ and $W_y = 0.51\text{mm}$. Sensor edge-to-edge spacing are $S_x = 3.42\text{mm}$ and $S_y = 2.51\text{mm}$.
4.2.3 Four sensors. Two dimensions. Asymmetric mask

Fig. 21 shows light intensities received by four two-dimensional sensors with an asymmetric mask with a larger air gap and a wider aperture margin, and Fig. 22 shows a case of a smaller air gap and a narrower aperture margin. Note the directionality, range, and sensitivity. Schematic is shown in Fig. 9.

![Figure 21: Received light intensity of four-dimensional sensors. Lux value is not normalized. Sensor lengths are $L_x = 0.39$mm and $L_y = 0.49$mm. Air gap is $H = 1.62$mm. Aperture margins are $W_x = 1.61$mm and $W_y = 1.51$mm. Sensor edge-to-edge spacing are $S_x = 3.42$mm and $S_y = 2.51$mm.](image)

Next plots show the effect of controlling the air gap $H$ while maintaining $W_x = L_x$, $W_y = L_y$ and fixed $S_x$, $S_y$. Note that the angle range $\theta_3$ increases with a smaller $H$ but with a larger nonlinearity.
Figure 22: Received light intensity of four-dimensional sensors. Lux value is not normalized. Sensor lengths are $L_x = 0.39\text{mm}$ and $L_y = 0.49\text{mm}$. Air gap is $H = 0.49\text{mm}$. Aperture margins are $W_x = 0.61\text{mm}$ and $W_y = 0.51\text{mm}$. Sensor edge-to-edge spacing are $S_x = 3.42\text{mm}$ and $S_y = 2.51\text{mm}$.
Figure 23: Received light intensity of four-dimensional sensors. Lux value is not normalized. Sensor lengths are $L_x = 0.39\text{mm}$ and $L_y = 0.49\text{mm}$. Air gap is $H = 0.1\text{mm}$. Aperture margins are $W_x = 0.39\text{mm}$ and $W_y = 0.49\text{mm}$. Sensor edge-to-edge spacing are $S_x = 3.42\text{mm}$ and $S_y = 2.51\text{mm}$. 
Figure 24: Received light intensity of four-dimensional sensors. Lux value is not normalized. Sensor lengths are $L_x = 0.39\text{mm}$ and $L_y = 0.49\text{mm}$. Air gap is $H = 0.2\text{mm}$. Aperture margins are $W_x = 0.39\text{mm}$ and $W_y = 0.49\text{mm}$. Sensor edge-to-edge spacing are $S_x = 3.42\text{mm}$ and $S_y = 2.51\text{mm}$. 

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Figure 25: Received light intensity of four-dimensional sensors. Lux value is not normalized. Sensor lengths are $L_x = 0.39\text{mm}$ and $L_y = 0.49\text{mm}$. Air gap is $H = 0.4\text{mm}$. Aperture margins are $W_x = 0.39\text{mm}$ and $W_y = 0.49\text{mm}$. Sensor edge-to-edge spacing are $S_x = 3.42\text{mm}$ and $S_y = 2.51\text{mm}$. 
Figure 26: Received light intensity of four-dimensional sensors. Lux value is not normalized. Sensor lengths are $L_x = 0.39\text{mm}$ and $L_y = 0.49\text{mm}$. Air gap is $H = 0.8\text{mm}$. Aperture margins are $W_x = 0.39\text{mm}$ and $W_y = 0.49\text{mm}$. Sensor edge-to-edge spacing are $S_x = 3.42\text{mm}$ and $S_y = 2.51\text{mm}$. 

(a) $I_3$

(b) $I_4$

(c) $I_1$

(d) $I_2$

(e) $I_1 - I_2$

(f) $I_1 - I_3$

(g) Ratio of $I_1$ and $I_2$

(h) Ratio of $I_1$ and $I_3$
Conclusion

This disclosure describes techniques to determine the angle of incident light using a planar array of ambient light sensors with asymmetric masks. The techniques have various applications in devices such as phones, tablets, laptops, etc., where they enable user interaction features.