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the speckles have been removed and the plausibility of transparent thin cells. Note how random binary phase mask (Fig. 1(b): pixel size 0.17 mm) directly from raw data such as from [5]. As a comb function with period $r = 2\pi/\lambda$ is the wave number.

Table 1: Our equation under different (approximated) forms as commonly seen formulas for each wavefront sensor. $\delta_t(x)$ is the Dirac function with period $\rho$ (the lenslet pitch).

<table>
<thead>
<tr>
<th>Name</th>
<th>Optics</th>
<th>Commonly seen formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shack-Hartmann</td>
<td>micro-lens array $I_f(r) = \delta_t(x) I_0(r)$</td>
<td>$I_f(r) = \lambda^2 \Gamma \nabla^2 I_0(r) = \delta_t(x) I_0(r)$</td>
</tr>
<tr>
<td>Lateral shearing</td>
<td>sinusoidal gratings (freq. $\omega$) $I_f(r) = \cos^2(\omega x) \cos^2(\omega y)$</td>
<td>$I_f(r) =</td>
</tr>
<tr>
<td>Curvature sensor</td>
<td>none</td>
<td>$I_f(r) = 1$</td>
</tr>
<tr>
<td>Coded wavefront sensor</td>
<td>random gratings $I_f(r)$ are speckles</td>
<td>$I_f(r) + \frac{2\pi}{\lambda} \nabla I_0(r) = \delta_t(x) I_0(r)$ in [5]; or our equation (this work)</td>
</tr>
</tbody>
</table>

Our theory reveals a potential to retrieve $|A(r)|^2$ and $\phi(r)$ directly from raw data such as from [5]. As a demonstration, by taking off the condenser lens, we turn an ordinary low-budget bright field microscope into a simultaneous intensity and phase microscopy, under collimated halogen lamp (HPLS245, Thorlabs) illumination. A prototype coded wavefront sensor is employed which consists of a bare sensor (1501M-USB-TE, Thorlabs) and a random binary phase mask (Fig. 1(b): pixel size 12.9 µm, either 0 or $\pi$ phase modulation at $\lambda = 550$ nm, placed $z = 1.43$ mm away from the sensor). Figure 2 shows simultaneous amplitude and phase recovery of transparent thin cells. Note how the speckles have been removed and the plausibility of the reconstructed smooth phase maps.

Figure 2: Quantitative phase imaging using our wavefront sensor. Images were taken under an $\times 100$ Mitutoyo plan apochromat objective, 0.70 NA. Inset close-up images show that the speckle patterns have been fully removed from the original raw data.

**References**


**Acknowledgments & Statement**

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