

Compact Single-Shot Incoherent Edge Detection With a Polarization-Multiplexed Metalens

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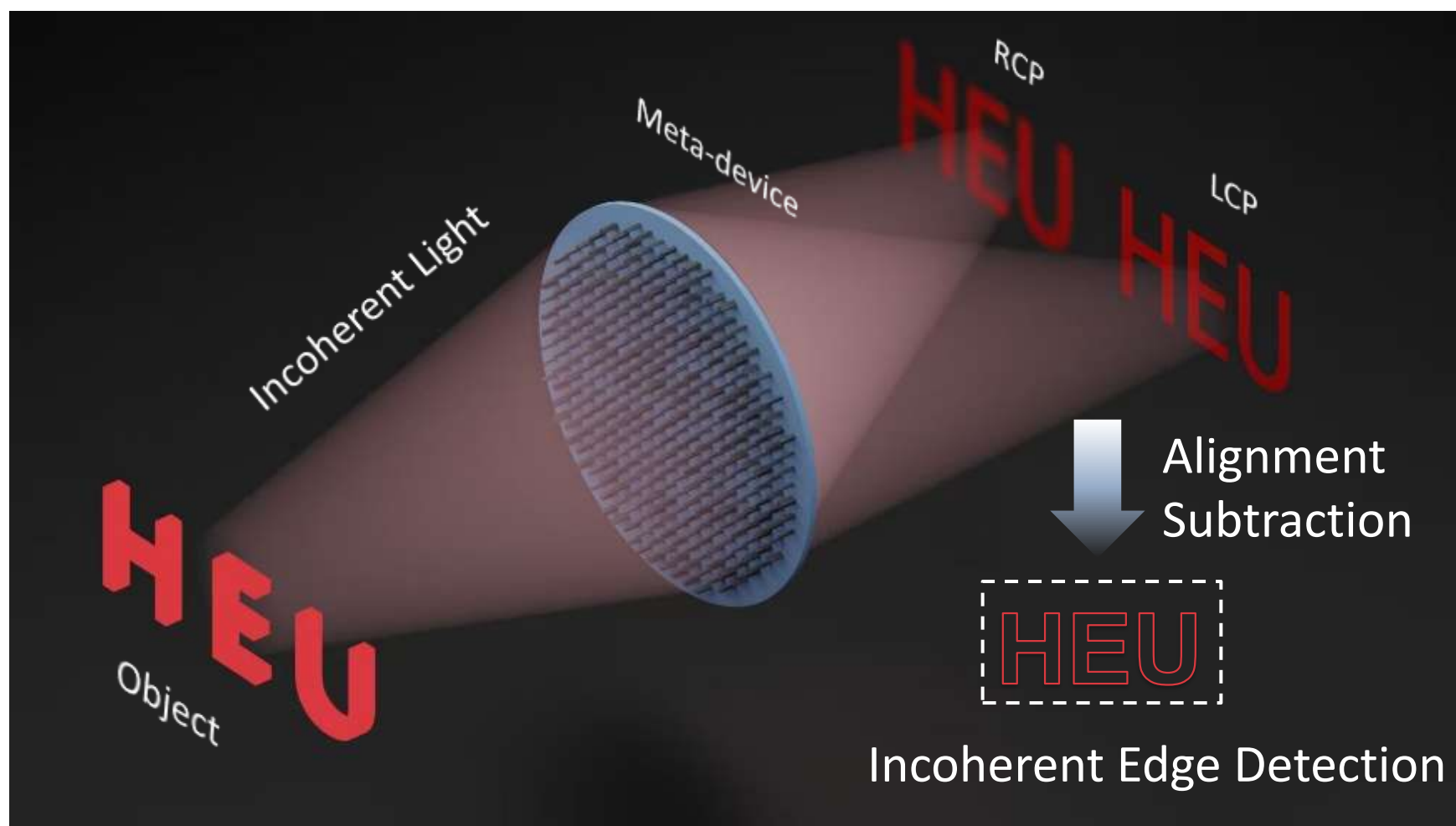
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Abstract

Edge detection under incoherent illumination is highly desirable for compact vision systems but remains challenging due to the lack of phase control and the difficulty of implementing high-pass filtering in intensity-based imaging. Here, we propose and experimentally demonstrate a polarization-sensitive metalens that enables single-shot incoherent edge detection by constructing a second-order high-pass optical transfer function (OTF). The metalens imparts distinct phase profiles to left- and right-handed circularly polarized components, producing a pair of spatially separated images that encode complementary object information. Through digital alignment and subtraction, an effective second-order high-pass OTF is realized, enabling robust edge enhancement while requiring only simple pixel-wise operations. We experimentally validate this approach using USAF resolution targets and further demonstrate a compact imaging module by directly integrating the metalens with a complementary metal-oxide-semiconductor (CMOS) sensor, enabling real-scene single-shot operation. This work establishes a practical optical preprocessing strategy for incoherent edge detection, providing a pathway toward miniaturized, low-power, and computation-efficient vision front-ends for machine vision, autonomous sensing, and portable imaging systems.

Principle and Design

Schematic of the Metalens



Effective OTF for Incoherent Edge Detection

Effective OTF for Incoherent Edge Detection

The differential responses of the two polarization channels synthesize an effective second-order high-pass OTF:

$$\mathcal{H}_{\text{eff}} = |\mathcal{H}_{\text{LCP}}(f_X, f_Y)| - |\mathcal{H}_{\text{RCP}}(f_X, f_Y)|.$$

Thus,

$$\mathcal{H}_{\text{eff}}(f_X, f_Y) = (c_{\text{LCP}} - c_{\text{RCP}})(f_X^2 + f_Y^2),$$

yielding the desired second-order high-pass response,

$$\mathcal{H}_{\text{eff}} \propto f_X^2 + f_Y^2$$

for incoherent edge enhancement.

Polarization-Dependent Phase Design

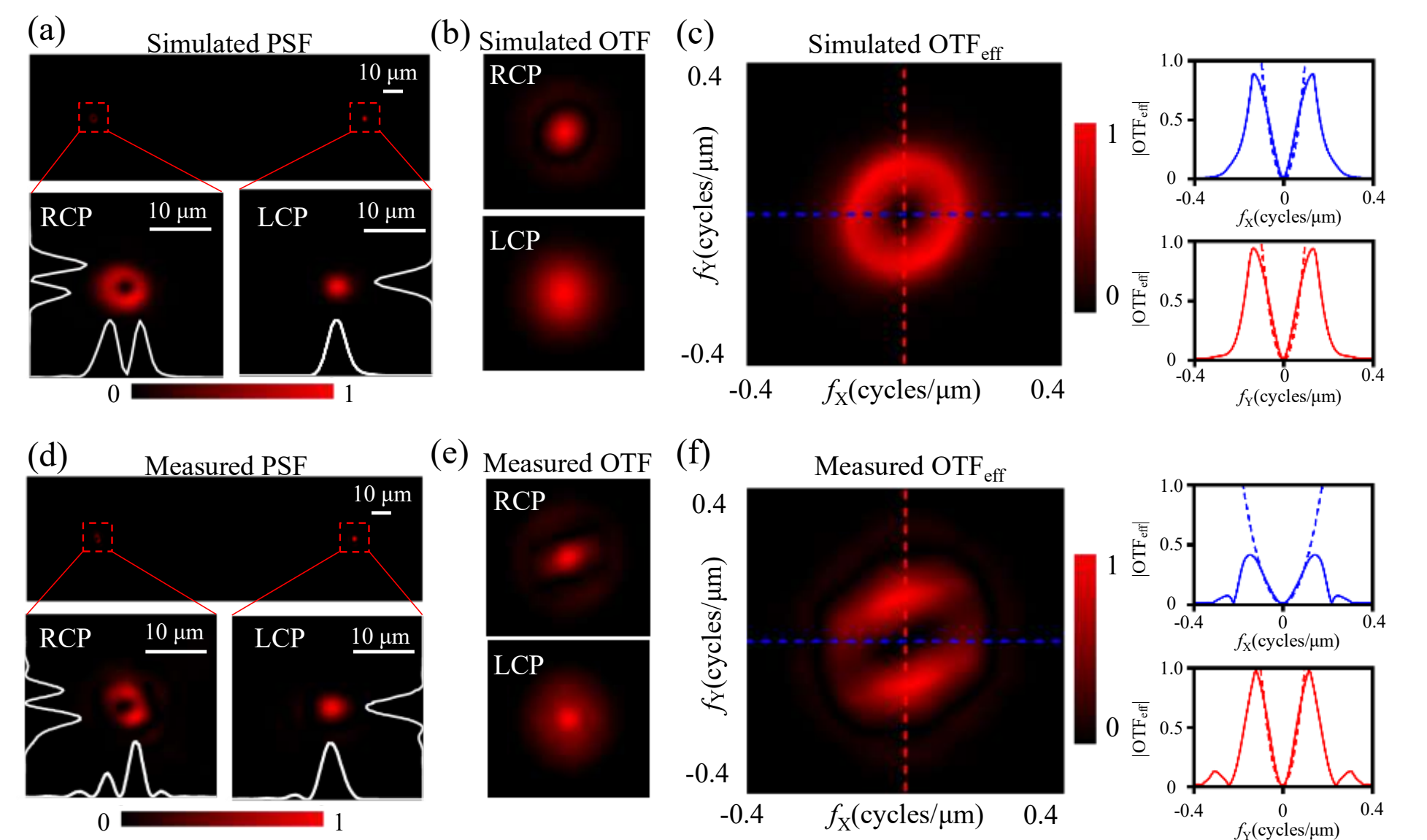
The phase distributions for the two circular polarization states are designed as

$$\begin{cases} \Phi_{\text{LCP}}(r, \theta) = \Phi_{\text{Parabolic}}(r, \theta) - \Phi_{\text{Gradient}}(r, \theta) \\ \Phi_{\text{RCP}}(r, \theta) = \Phi_{\text{Parabolic}}(r, \theta) + \Phi_{\text{Gradient}}(r, \theta) + \Phi_{\text{Spiral}}(r, \theta) \end{cases}$$

The constituent phase terms are $\Phi_{\text{Parabolic}}(r, \theta) = -k_0 r^2 / 2f$, $\Phi_{\text{Spiral}}(r, \theta) = \theta$, and $\Phi_{\text{Gradient}}(r, \theta) = -k_0 r \sin \alpha \cos \theta$. Here, $\alpha = 4^\circ$ is the deflection angle, and $f = 1.93\text{mm}$.

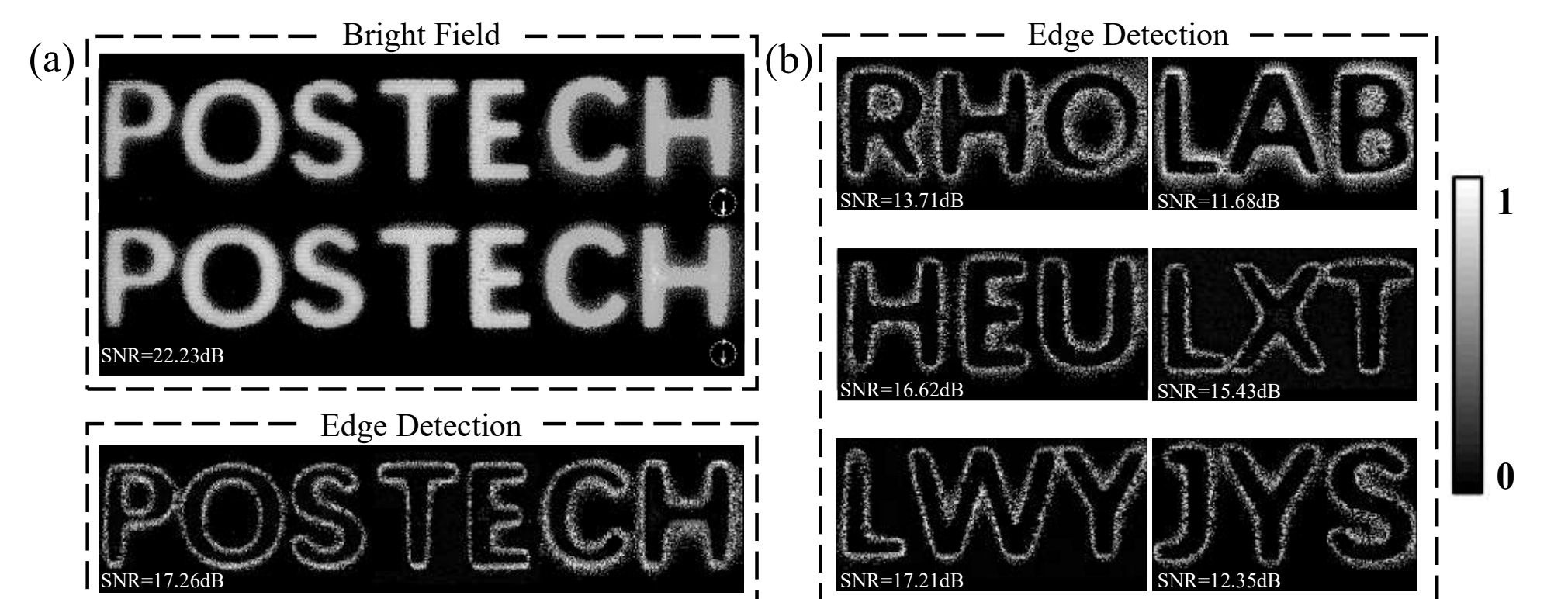
Result and Discussion

Polarization-Dependent Optical Characterization



Effective OTF: Measured differential response confirms second-order high-pass filtering.

Compact Metalens-CMOS Imaging



Integrated imaging: Metalens and CMOS sensor enable compact real-scene single-shot operation.

Demonstration: Clear edge-enhanced characters are recovered under incoherent illumination.