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Beam Shaping of VCSEL-Arrays with Collimating Random Microlens Arrays

Motivation

VCSEL arrays are compact and cost-efficient light sources widely used in active imaging systems due to their high modulation bandwidth, high optical power and narrow spectral band. However, they emit divergent, circular Gaussian beams that must be reshaped to match the rectangular field of view (FOV) of the imaging sensor and to follow a tailored irradiance distribution—typically a "batwing profile" that compensates for vignetting.

Random Microlens Arrays (RMLAs) represent the state of the art in passive beam shaping. When illuminated with collimated light, they can efficiently generate rectangular batwing profiles (Fig. 1a). However, VCSELs emit uncollimated light, which leads to blurred edges in the projected profile and reduced spatial resolution (Fig. 1b), resulting in lower system efficiency as light spills outside the desired FOV.[1]

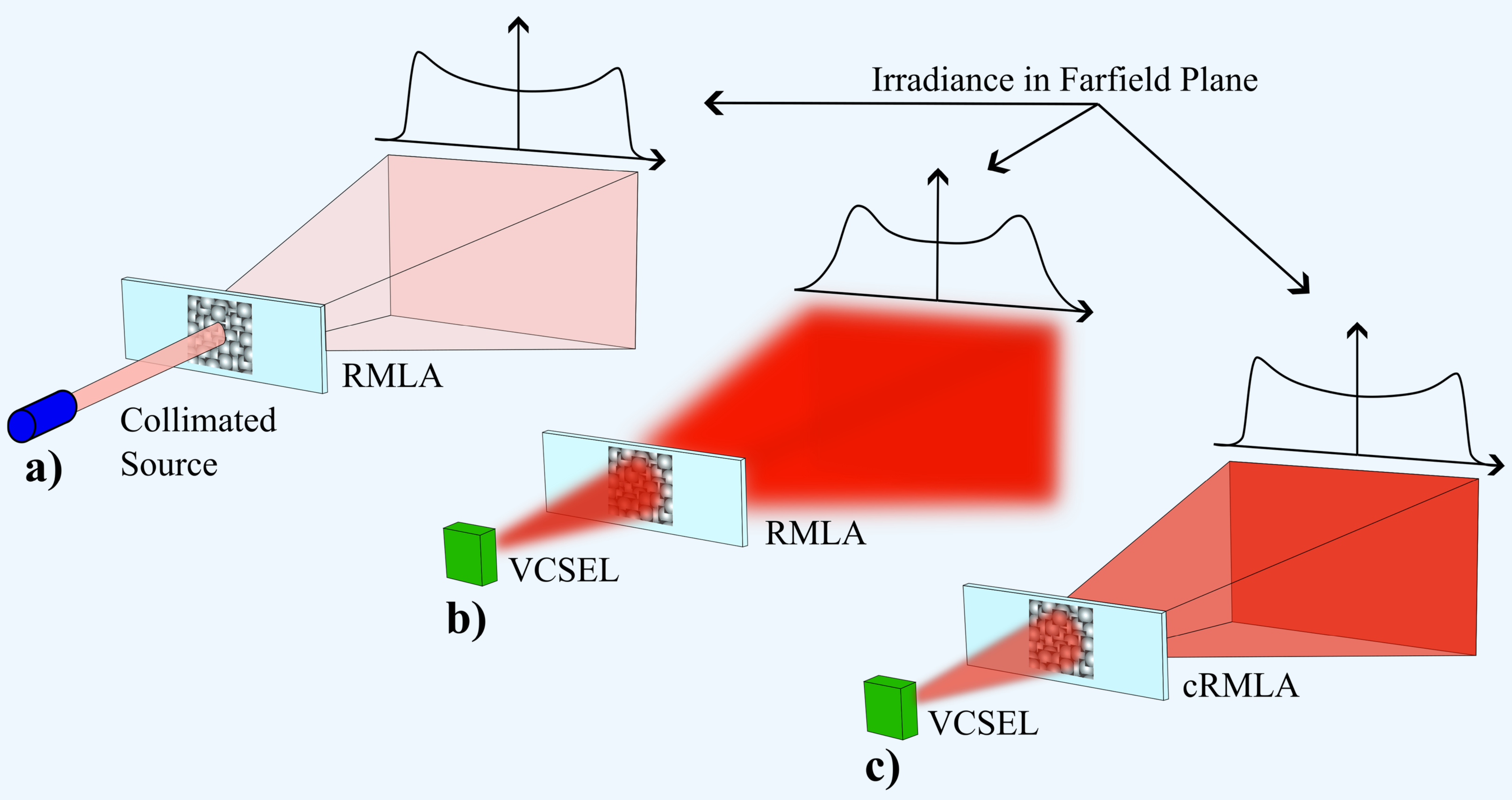

Fig 1: Different Beam Shaping Setups: a) Collimated Source with RMLA b) VCSEL-Array with RMLA c) VCSEL with cRMLA

We propose the Collimating Random Microlens Array (cRMLA)—an integrated optical element that combines beam collimation and shaping in a single surface. This approach improves beam sharpness and increases optical efficiency under VCSEL illumination (Fig. 1c).

Structure Design

The design of the cRMLA follows a three-step process, similar to the design of an RMLA[2]: First, an individual microlens is numerically optimized to direct light toward a desired target distribution. This design step uses an iterative optimization approach to fine-tune the surface profile for high efficiency and minimal aberrations (Fig. 2 a).

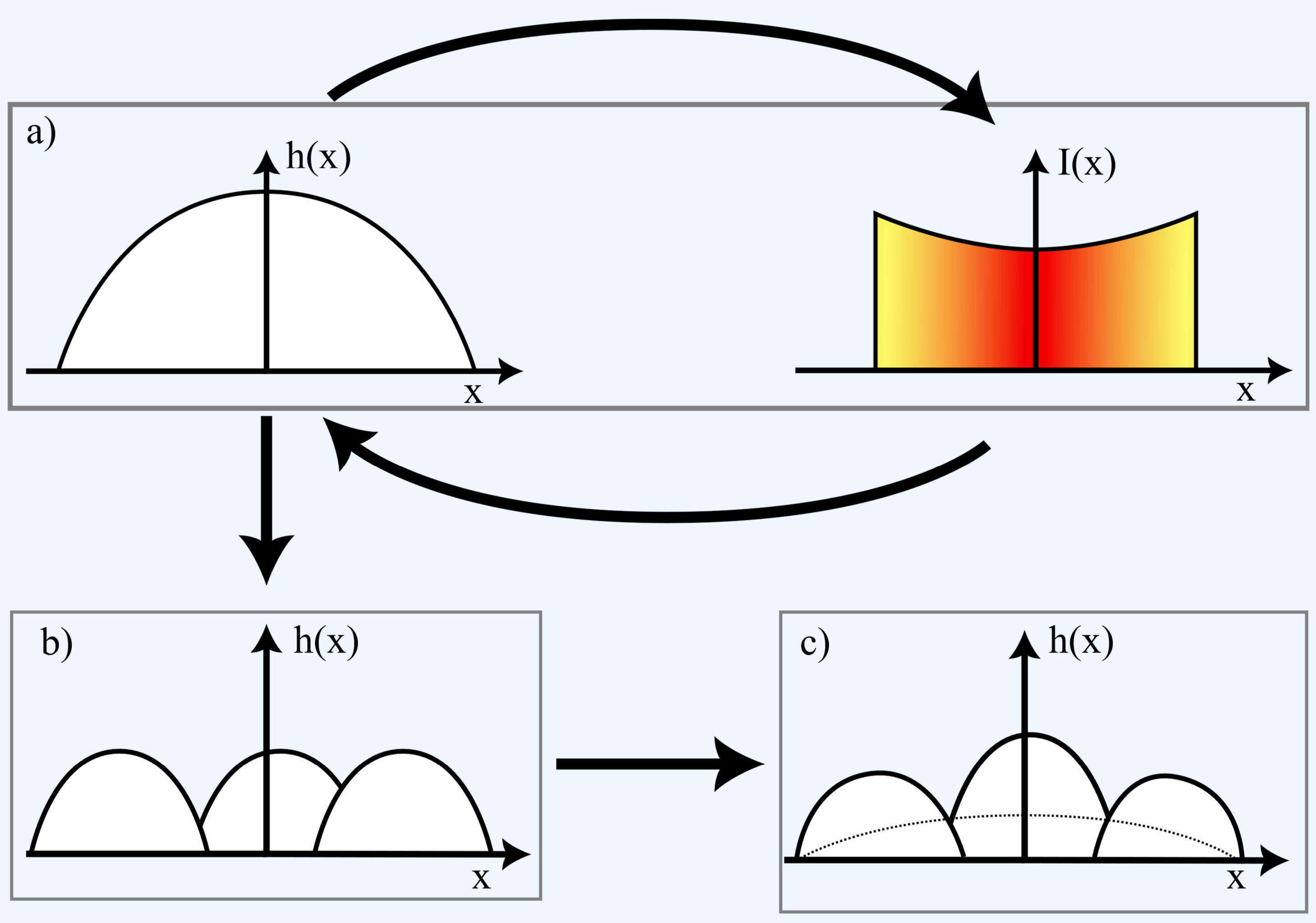

Fig 2: Design Procedure of the cRMLA: First, a single microlens is designed in an iterative process (a). Next, multiple lenses are placed in a randomized array (b). Lastly, a collimating lens profile is added to the RMLA surface (c).

Next, multiple copies are placed in a randomized layout to form a complete RMLA (Fig. 2 b). The randomization eliminates interference artifacts and promotes a smooth output profile.

Finally, a collimating lens surface is superimposed onto the RMLA structure (Fig. 2 c). This surface collimates the VCSEL light, improving spatial resolution and system efficiency.[1]

Fabrication and Verification

The designed cRMLA and an RMLA are fabricated using a Two Photon Polymerization (TPP) photolithography system. The height profiles of the fabricated structures are characterized using a confocal microscope. A comparison between the designed and measured profile of a single lens in the RMLA is presented in Fig. 3.

The steep edges could not be fully captured due to low reflectivity, but across the measurable area, the RMS deviation is (270 ± 10) nm, indicating good agreement between design and fabrication.

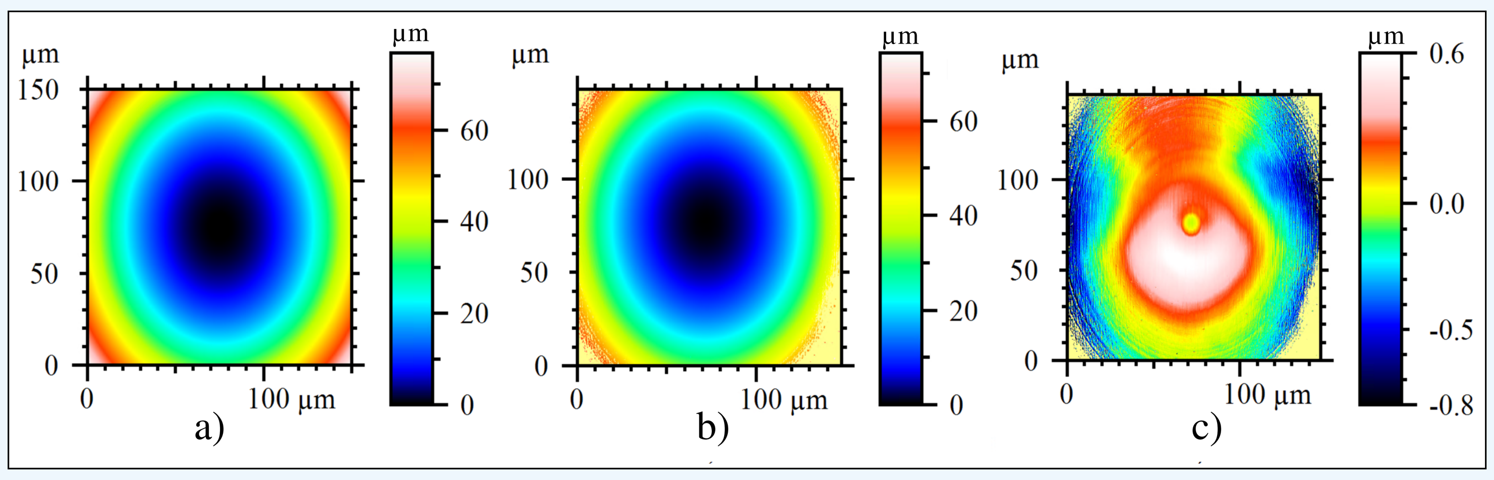

Fig 3: Measurement of a Single Microlens: a) designed height profile, b) measured height profile c) difference between height profiles

Beam Profile Measurements

To evaluate the performance of the fabricated beam shaping elements, the far-field irradiance distribution is measured using a diffuse screen as shown in Fig. 4. The screen is imaged with a calibrated camera system, which corrects for both the vignetting of the camera and the scattering characteristics of the screen.[3] Calibration is performed using a reference light source with a known irradiance distribution.

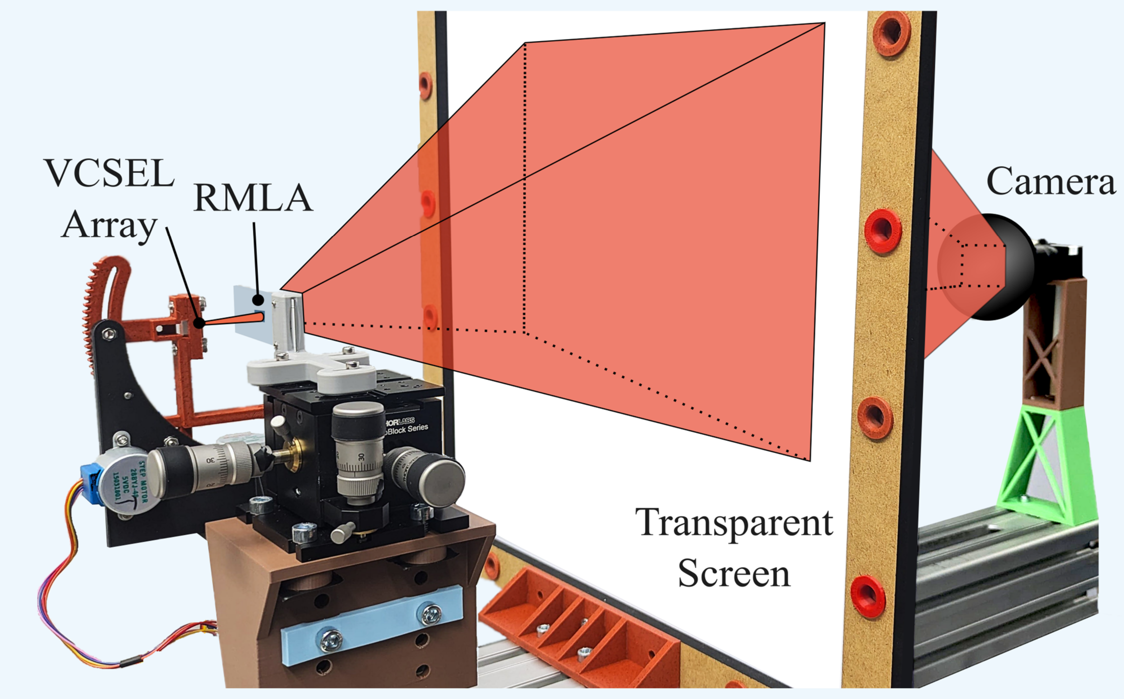

Fig 4: Beam Profile Measurement Setup: The VCSEL-array illuminates the RMLA, which reshapes the beam. The reshaped beam is transmitted through the screen and captured by the camera.

Results

Three beam shaping elements are compared: a commercial RMLA, a self-fabricated RMLA, and the proposed cRMLA. The resulting beam profiles are shown in Figure 4 (a–c). The cRMLA demonstrates significantly higher spatial resolution than the RMLAs, validating the effect of integrated collimation. However, the expected batwing distribution is less pronounced in the cRMLA measurement. The origin of this discrepancy is likely caused by an approximation made in the integration of the collimating lens.

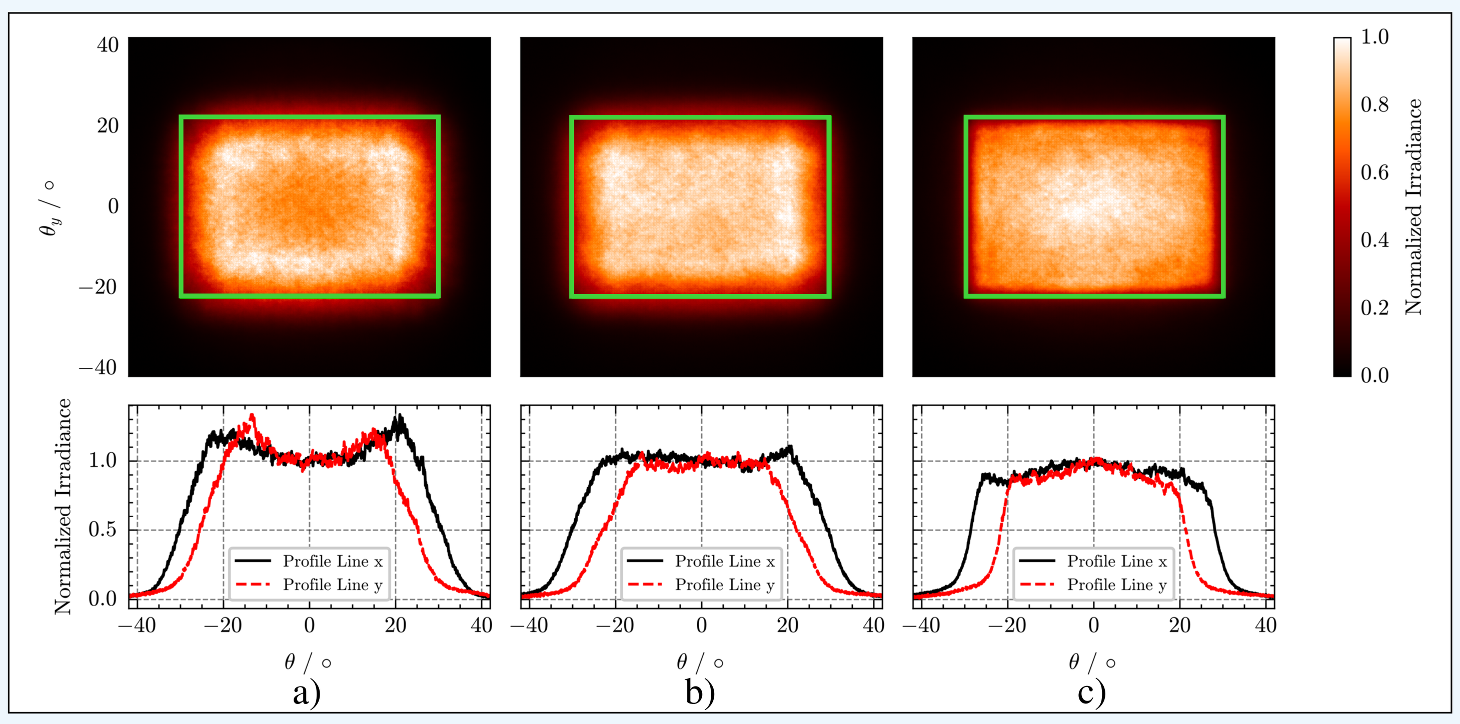

Fig 5: Measured Beam Profiles: Top: measured profiles with target field (green). Bottom: corresponding line profiles. a) VCSEL with commercial RMLA, b) with our RMLA, c) with our cRMLA.

1: Elias Ellingen, "Design, Fabrication and Verification of Microoptics for Illumination Beamshaping in Active Imaging Systems", Master Thesis, Hochschule Bonn-Rhein-Sieg, 08/2024

2: T. R. Sales, "Bandlimited illumination with engineered diffusers," Advanced Optical Technologies, vol. 1, no. 3, pp. 127–134, 2012.

3: Titus Lange, "Positionierung und Qualitätsbewertung von Mikrooptiken für laserbasierte optische Sensorsysteme", Bachelors Thesis, Hochschule Bonn-Rhein-Sieg, 03/2025

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