Electronic Supplementary Information

Optofluidic Lens with Low Spherical and Low Field Curvature Aberrations

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Coordinate transformation of the Maxwell's Fisheye lens

Figure S1: Light propagation in (a) circular fisheye lens and (b) rectangular optofluidic lens.

Two-step coordinate transformations are conducted to transform the circular fisheye lens into a rectangular optofluidic lens. The index relationship between the two lenses is expressed as [1],

$$n(z) = \left| \frac{DN(z,k)}{1 + CN(z,k)} \right| \cdot n_{circle}$$
(S1)

where $z = x + i \cdot y$ is the complex number that represents the complex coordinate systems, n_{circle} is the index profile of the circular fisheye lens shown in Eq. (1), and *k* is a function related to the geometry of the rectangle. It can be numerically proven that *k* is approaching zero if the height of the rectangle is much larger than the width. Therefore, Eq. (S1) can be simplified as,

$$n(z) = \frac{n_0}{2} \cdot \operatorname{sech}(\alpha \cdot y)$$
(S2)

where n_0 is the highest index value, α is a constant related to lens geometry. Figure S1(a) and (b) illustrate the light propagation in the circular fisheye lens and the rectangular optofluidic lens.



Maximum divergence angle of optofluidic lens

Figure S2: The spatial relationship between (a) the circular fisheye lens and (b) the optofluidic lens. (c - d) Schematic illustration of the light propagation in the two lenses with index approximation.

The ideal index profile of the optofluidic lens is a hyperbolic secant profile ranging from 0 to $n_0/2$. However, the index of liquid medium generally ranges from 1.332 to 1.5. As a result, the top and bottom regions of the rectangular lens (white region) have to be discarded as shown in Figure S2(a). Based on the relationship of the two coordinate systems, the discarded region corresponds to the two pole regions of the circle in Figure S2(b). When the incident angle of light beams is sufficiently large to make the light beam reach the discarded regions, the light cannot be focused anymore as illustrated in Figure S2(c-d). Therefore, the index approximation reduces the maximum divergence angle. The spatial relationship indicates that higher index contrast is favored to reduce the discarded regions and hence to achieve a larger maximum divergence angle.



Optofluidic lens with different widths

Figure S3: (a) Ray tracing simulation of light beams with different channel widths. (b) Simulated focal length as a function of channel widths with the core/cladding ratio of 2.25.

Ray tracing results



Figure S4: Ray tracing simulation of light beams with different divergence angles in the (a) optofluidic GRIN lens and (b) optofluidic lens.



Figure S5: Ray tracing simulation of light beams with different off-center positions in the (a) optofluidic GRIN lens and (b) optofluidic lens.

Refractive index measurement



Figure S6: Pixel intensity as a function of the mass fraction of ethylene glycol.

Fluorescent dye (Rhodamine 6G, Concentration: $\sim 10^{-6}$ g/mL) is added into pure ethylene glycol. The ethylene glycol is mixed with deionized water to obtain 20%, 40%, 60% and 80% ethylene glycol solutions. Then, the solutions are applied into the microchannel for pixel intensity quantification. The pixel intensity is linearly proportional to the mass fraction of the ethylene glycol as shown in Figure S6. The percentage of nonlinearity can be expressed as [3],

$$nonlinearity(\%) = \frac{(MaxPositiveDerivation + MaxNegativeDerivation)}{MaxSignal} \times 100, \quad (S3)$$

which is 6% based on the experimental data. The nonlinearity is mainly induced by the nonlinearity of the CCD camera and the experimental errors during solution preparation. Like majority of chemicals, the refractive index of ethylene glycol is also linearly proportional to its mass fraction. Therefore, we can infer that the refractive index is in a linear relationship with the captured pixel intensity.

The index profile in the mixing chamber and the optofluidic chamber is measured as shown in Figure S8. It illustrates that the discrete refractive indices evolve into a continuous hyperbolic secant profile in the mixing chamber. Subsequently, the refractive index profile keeps invariant in the optofluidic chamber due to the high flow rates.



Figure S7: (a) Fluorescent image of index profile at different positions. (b) Measured refractive index at x_1 , x_2 and x_3 , respectively.

Beam Profile of Laser Light



Figure S8: Captured image of the beam profile from the single-mode fiber.

The light beam profile emitted from a single mode fiber is measured using a beam profiler (SP503U, Ophir-spiricon). Figure S6 shows that the light beam (distance to fiber tip: 31.2 mm) follows a Gaussian beam profile and the beam divergence angle is measured as 12.13 degrees.

Calculation of Spherical Aberration



Figure S9: Schematic illustration of spherical aberration measurement.

As shown in Figure S9, spherical aberration δ is defined as the distance between the paraxial focus (green dot) and the peripheral focus (red dot). The best focal point (black spot) is the position with the maximum light intensity. The distance between the best focal point and paraxial focus is proportional to the spherical aberration δ as [4],

$$\delta = \alpha \cdot \Delta l \tag{S4}$$

where α is 0.75 in this case. To calculate the spherical aberration, the focal length of the paraxial rays is estimated as the y-intersection of the focal position curve in Figure 5(f). The focal length of the best focal point is the measured by plotting the intensity profile along the optical axis and finding the position with maximum intensity.

References

- M. Schmiele, V.S. Varma, C. Rockstuhl, F. Lederer, Designing optical elements from isotropic materials by using transformation optics, Phys Rev A, 81(2010).
- [2] F. M. Zehentbauer, C. Moretto, R. Stephen, T. Thevar, J. R. Gilchrist, D. Pokrajac, K. L. Richard, J. Kiefer, Fluorescence spectroscopy of Rhodamine 6G: Concentration and solvent effects, Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 121(2014), 147-151.
- [3] Holst, C. Gerald, CCD arrays, cameras, and displays, Vol. 38. Bellingham, WA: SPIE Optical Engineering Press, 1998.
- [4] J.C. Wyant, K. Creath, Basic wavefront aberration theory for optical metrology, Applied optics and optical engineering, 11(1992) 2.