Optical phase conjugation assisted scattering lens: variable focusing and 3D patterning

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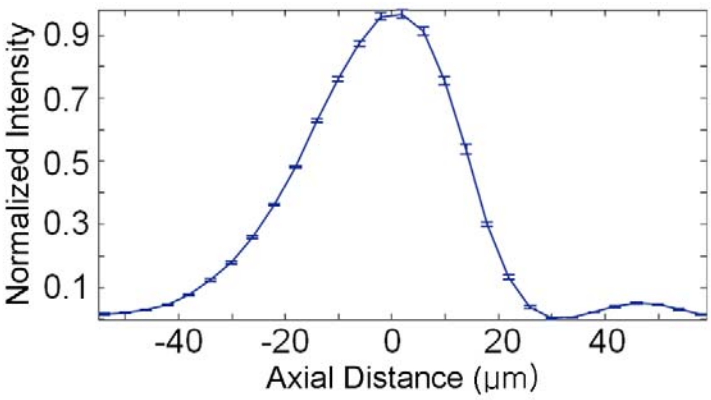
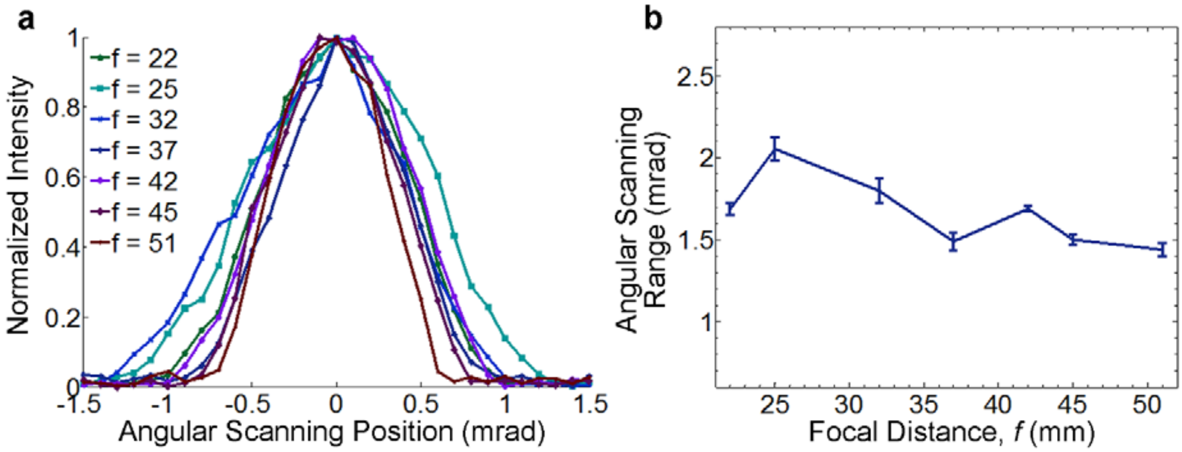
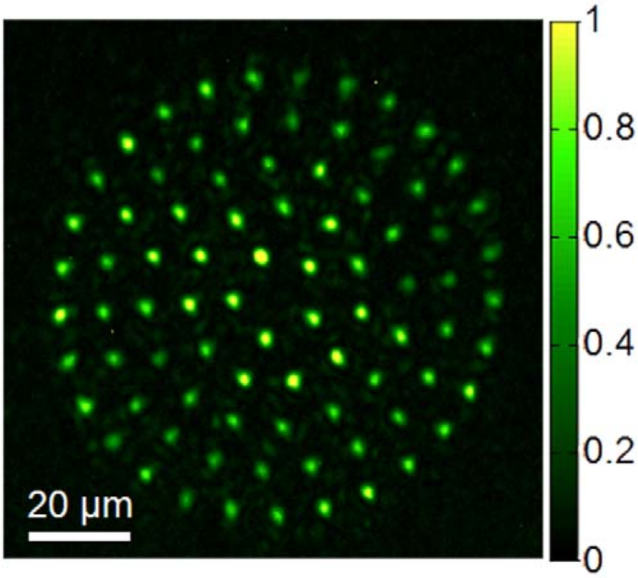
Supplementary Figures



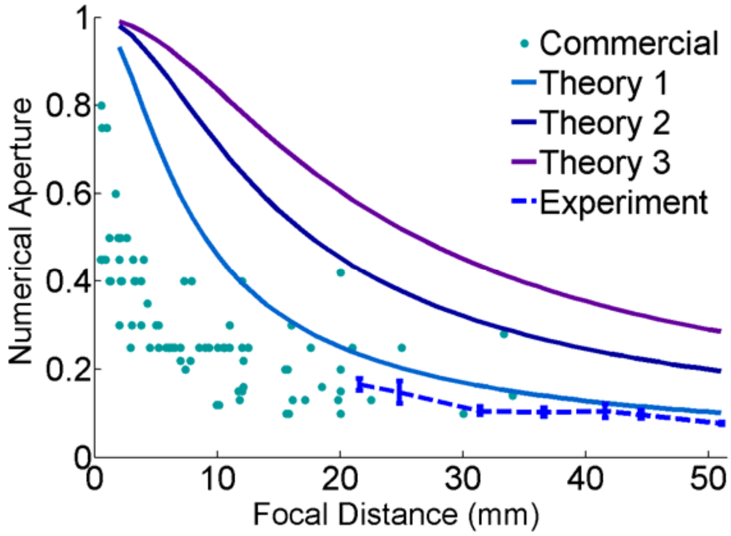
Supplementary Figure S1 | Axial intensity profile of the focal spot created at focal distance of 22 mm. Normalized peak intensity of the focal spot is measured at different axial distances. The full width at half maximum of the axial intensity profile is ~ 33 μm.



Supplementary Figure S2 | Angular scanning range of the OPC-assisted scattering lens. (a) Normalized peak intensity of the focal spot at different tilt angles and focal distances. (b) Theoretical and experimental full width at $1/e^2$ of the intensity profile at different focal distances. The angular scanning range is ~1.6±0.2 milliradians regardless of focal distance.



Supplementary Figure S3 | Generation of light pattern composed of 83 multiple foci. 83 multiple foci are simultaneously created at the focal distance of 37 mm. The enhancement factor η_K is ~20-34.



Supplementary Figure S4 | Trade-off relationship between NA and focal distance (working distances for objective lenses). Green circles illustrate the trade-off relationship in commercially available objective lenses. The blue dotted line shows the experimental data acquired from our scattering lens in the current study. The cyan solid line indicates the theoretical trade-off relationship of our scattering lens. Navy and purple solid lines represent the predicted focal distance-NA curves of scattering lenses with aperture size of 20 and 30 mm, respectively.

Supplementary Note

Supplementary Note 1 | Impact of thickness of scattering medium.

Since the phase conjugation plane is optically located on the surface of scattering lens, we are able to laterally move the focused spot by simply adding a linear phase gradient on the conjugated wavefront. Theoretically, the short range correlation (memory effect) has the following dependence on the tilting angle [1,2]:

$$C(\theta) \approx \left[\frac{(2\pi\theta L/\lambda)}{\sinh(2\pi\theta L/\lambda)} \right]^2 \quad \text{(S.1)}$$

when the tilting angle is small. θ is the tilting angle and L is the thickness of scattering lens. Thus, the intensity of the spot is dropped by $1/e^2$ when the tilt angle is

$$\theta_{1/e^2} \approx 0.43\lambda/L \quad \text{(S.2)}$$

Then, the corresponding scanning range (Δ) is given by

$$\Delta \approx 2\theta_{1/e^2} f \approx 0.86\lambda f/L \quad \text{(S.3)}$$

where f is the focal distance. That is, the lateral scanning range linearly increases with the focal distance, f .

Supplementary References

1. S. Feng, C. Kane, P. Lee, and A. Stone, "Correlations and fluctuations of coherent wave transmission through disordered media," Phys. Rev. Lett. **61**, 834–837 (1988).
2. I. Freund, M. Rosenbluh, and S. Feng, "Memory effects in propagation of optical waves through disordered media," Phys. Rev. Lett. **61**, 2328–2331 (1988).