A novel axicon-structured lens

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A design method based on the theory of structured lenses gives a new type of axicon with long focal depth.

Optical systems with long focal depths can tolerate wide out of focus values, which in turn provide wider measurement ranges when observing deep samples. Axicon lenses have conical surfaces and can generate diffraction-free beams, which provides a good way to extend the focal depth of optical systems used in microscopy, alignment, imaging, and optical interconnection. Their design has drawn great research interest in recent years, and researchers have proposed design methods for some novel applications.\textsuperscript{1, 2} Here, we discuss the design of a new type of axicon, with a long focal depth, based on the design theory of structured lenses.

Our axicon is constructed by creating square holes in a single layer of silver film (see Figure 1). The electric field in the square holes can be derived according to the Helmholtz equation and the boundary conditions.\textsuperscript{3} By appropriately arranging the holes, which are the same distance from the lens center, the light rays passing through are focused at the same point on the propagation axis.

When designing the axicon lens, we first determined the phase function of the structured lens with long focal depth using the theory of nondiffractive Bessel beams of uniform intensity. Next, we calculated the relationship between the length of the sides of the square holes and phase retardation. This is important because in modulating phase retardation the propagation behavior can be controlled by the axicon-structured lens. Finally, we expressed the phase function based on the location and dimensional parameters of the holes.

We designed an IR lens suitable for wavelengths of 10.6\textmu m, with a focal length of 1000mm, focal depth larger than 20mm, and aperture of 100mm. A silver film with a thickness of 19.08\textmu m, which is 1.8x\textlambda (where \textlambda is the wavelength), is deposited on the surface of a germanium substrate.

Figure 2(a) shows the relationship between the side lengths of the squares and phase retardation. We can see that holes with sides 5.5–9.6\textmu m long can modulate phase retardations of \pi\sim3\pi. Since all of the phase retardations in this case can be normalized into the range of \pi\sim3\pi, the axicon can be realized with square holes that have side lengths between 5.5–9.6\textmu m. Figure 2(b) shows the structured lens calculated based on the phase requirement distribution and the relationship given in Figure 2(a). The lens can be expressed as variable hole sizes, gradually increasing from red to blue as denoted in zoom range.

Numerical simulations yielded the intensity distribution along the optical axis (i.e., the z axis) of the lens: see Figure 2(c). Figure 2(d) shows the same distribution and demonstrates the focal range of the lens, which indicates 25mm (full width at half maximum) of the focal depth can be achieved, satisfying the requirement. We also carried out a control calculation for a common lens with the same parameters, resulting in a focal depth of 3.78mm. Therefore, the focal depth for our axicon lens has been extended almost seven times compared to a common lens with the same diameter and focal length.

In summary, our method for constructing elements with complicated phase distribution offers an easy route to realize a novel type of an axicon lens with long focal depth. The construction of this lens is different from a classical axicon. It involves making holes in a metallic film, which could be achieved using a micro-fabrication method. In future work, we will fabricate the
lenses and assess them broadly. Their compact size, light weight, and high degree of design flexibility make them ideal for many modern optical systems.

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References