Engineering focal field properties in optical microscopy

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A new method of controlling polarization under the objective lens could unlock hidden information and provide better 3D perspective.

Optical microscopy is an indispensable tool for many industries and scientific disciplines due to its ability to provide abundant information without damaging the sample. Examples include biomedical diagnostics, product inspection, and materials characterization. Rapid advances in modern techniques have meant researchers can now visualize microscopic structures and processes in unprecedented detail. To obtain high-quality images, powerful objective lenses with a high numerical aperture are used. This approach may be further enhanced by optimizing the optical focal spot of the lens, which involves honing the distribution of light intensity and taking into account the polarization of the focal field.

Polarization is an important parameter in optical microscopy because the physical properties of many internal structures in a sample are directionally dependent. Consequently, their different responses to polarization provide a sensitive way to visualize these structures in detail. Full control of the polarization state under the microscope would be extremely valuable for researchers, significantly expanding the potential uses of optical microscopy. However, until now this has not been possible owing to the lack of a systematic way of designing the pupil polarization distribution and difficulties in synthesizing complex polarization patterns.

Recently, we developed a method to engineer the properties of the focal field of the microscope, including the state of polarization under high-power focusing. Our approach is two-pronged, combining the theory of antenna radiation with a technique for the vectorial diffraction of focusing systems described by Richards and Wolf. Working backwards from observed data, we have been able to determine the input values required for the microscope to generate focal fields with desired properties.1–4

In one study, we generated an optical needle field.4 Here, the electric field is polarized along the optical axis of the objective lens.5 This provides a extremely long depth of focus that enhances 3D perspective. It is valuable for several areas of research, including laser cutting and optical trapping of nanoparticles. To obtain the optical needle field, we calculated the emission pattern of a linear electric dipole array distributed along the optical axis at the pupil plane of the lens. We then reversed the propagation of this field and used it as the illumination to reconstruct the source field of the dipole array.

We subsequently adopted the Richards-Wolf vectorial diffraction method to demonstrate the validity of our method (see Figure 1). Using numerical modeling, we calculated that a depth of focus up to \(>8\lambda\) (where \(\lambda\) is the wavelength of light) is obtainable. Throughout this depth of focus, the engineered focal field maintains a diffraction-limited transverse spot size (\(<0.43\lambda\)) with very high longitudinal polarization purity, meaning that up to 87% of the energy density stored in the electric field is polarized along the optical axis. We also showed that the depth of focus can be further increased by using a dipole array with more dipole elements.

We have used the creation of an optical needle field to illustrate the capability of our method. This approach may be Continued on next page
further extended to construct other, more general focal fields with specific intensity and polarization distributions as desired. In the future, we anticipate that our method will allow us to obtain new information on samples and that it will have important applications in many fields, including optical manipulation, micromachining, and photolithography. We are currently developing techniques to synthesize the necessary pupil-plane illumination distribution. These techniques will then be integrated into commercial microscopes to demonstrate the benefits of full polarization control within the focus.

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References