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Structuring the three electric field components of light

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Unless the beam's transverse electric field components are divergence-free in the two-dimensional transverse plane [1], tightly focused light typically leads to a non-negligible longitudinal electric field component [2], where the terms longitudinal and transverse electric field components refer to the components of the electric field that are parallel or perpendicular, respectively, to the direction of the mean Poynting flux. Having a longitudinal electric field component does not add a new degree of freedom, in the sense that all components of the electric and magnetic fields are still fixed by prescribing two electric field components in a plane. However, it is the electric field component *parallel* to the direction of the Poynting flux that makes it somewhat special.

In this contribution we investigate simultaneous structuring of all three electric field components, and in particular we demonstrate that complex light shaping of the longitudinal component is indeed possible. For the proposed algorithm, a two-dimensional Helmholtz decomposition of the transverse electric field components in the transverse plane is key. The Helmholtz decomposition allows the generalization of the notion of "radial" and "azimuthal" polarization in the following way: *radial polarization* corresponds to an electric field that is "curl-free" in the transverse plane — which as we shall see can be interpreted as a flow solely due to sinks and sources without vorticity — and is the part of the field that gives rise to the longitudinal polarization. An *azimuthally polarized* electric field is "divergence-free" in the transverse plane — analogously to a flow solely due to vorticity without any sinks or sources — and does not give rise to any longitudinal electric field component. Employing those polarization states turns out to be very useful for computing numerically exact solutions to Maxwell's equations with structured electric field components, and moreover facilitates an intuitive understanding of tightly focused vector beams through straightforward analogies to electrostatics, magnetostatics and fluid dynamics.

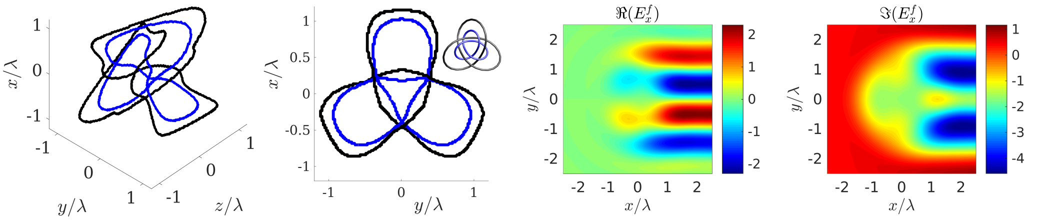

Fig. 1 Vortex lines forming two linked trefoils in different components of the electric field: The blue line represents the vortex line in the transverse component E_y, the black line the vortex line in the longitudinal component E_z. The corresponding (semi-infinite) profiles in E_x at $z = 0$ (focus) are shown in the right panels.

In Fig. 1 we demonstrate the tremendous capabilities of our algorithm by creating knotted vortex lines in the longitudinal and one transverse electric field component (E_y) simultaneously. The topology of the two knots we envisage is sketched in the two left panels: the vortex lines of the E_y and E_z components form two linked trefoil knots. Even though at first glance this example may seem somewhat contrived, it highlights that vortex lines in different electric field components can be chosen to be arbitrarily close without reconnecting. This is a priori not possible for vortex lines in a single electric field component, which could be of importance when considering inscribing these vortex lines onto matter. The corresponding transverse electric field component E_x, which is fully determined by our algorithm and shown in the right panels of Fig. 1, is formally nonzero on a semi-infinite interval, and has to be attenuated in practise by, e.g., a sufficiently wide super-Gaussian profile. We checked that such procedure does not affect the propagation of the components of interest close to the optical axis.

We believe that our findings will broaden the range of accessible vector beams extensively and trigger further theoretical and experimental investigations involving structured light.

References

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