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Berry Phase, Polarization, and Point Spread Function in High Etendue Optical Systems

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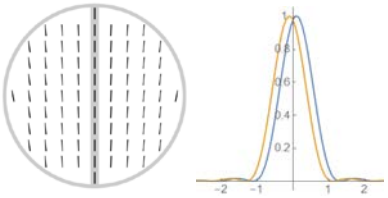
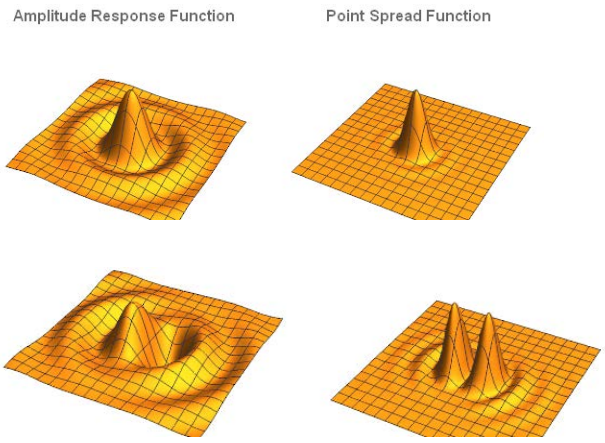
When light rays propagate through optical systems, the polarization state folds at each interface as the light changes direction on reflection or refraction. For meridional rays the light's phase is not affected by these direction changes. But for skew rays which spiral around the optical axis in either a clockwise, for one side of the pupil, or a counterclockwise sense for the other side, a phase change occurs oppositely for right and left circularly polarized light. In quantum mechanics this is known as the Berry phase, arising from the parallel transport of vectors along great circles over a sphere. This phase change is like optical activity and circular retardance, but is a geometrical effect, no optical path difference is involved.

The variation of the Berry phase across a wavefront is known as "skew aberration" since it occurs for skew, but not marginal rays.[i] The effect is small in typical optical systems, but as the field of view increases and as the numerical aperture increases, i.e. as the etendue increases, such as in microlithography and microscopy, the skew aberration becomes significant.[ii] In a skew aberration expansion, as the source moves off-axis the dominant term is a linear variation of circular retardance perpendicular to the meridional plane. The effect on circularly polarized light is a tangential shift between the right and left circularly polarized Point Spread Function (PSF) components. The effect on linearly polarized light is a cross polarized term whose amplitude is the first derivative of the coherent PSF, for example the derivative of the Airy function.



(Left) Variation of the Berry phase across the pupil off axis. Gray –meridional plane. (Right) Effect on left and right circularly polarized light is a PSF shift in opposite directions.



PSF for linearly polarized light: (Top) co-polarized, (Bottom) weak cross-polarized component is first derivative of Airy function taken perpendicular to meridional plane.

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[i] Skew aberration: a form of polarization aberration, G.Yun, K. Crabtree, R. Chipman, Opt. Lett. **36**, 4062-4064 (2011).

[ii] The point spread function in paraxial optics, R.A.Chipman, W.S.T.Lam, *Proc. SPIE*, **9578-03**, 2015.