Simulation of secondary maxima of highly focused optical pulses in the focal point

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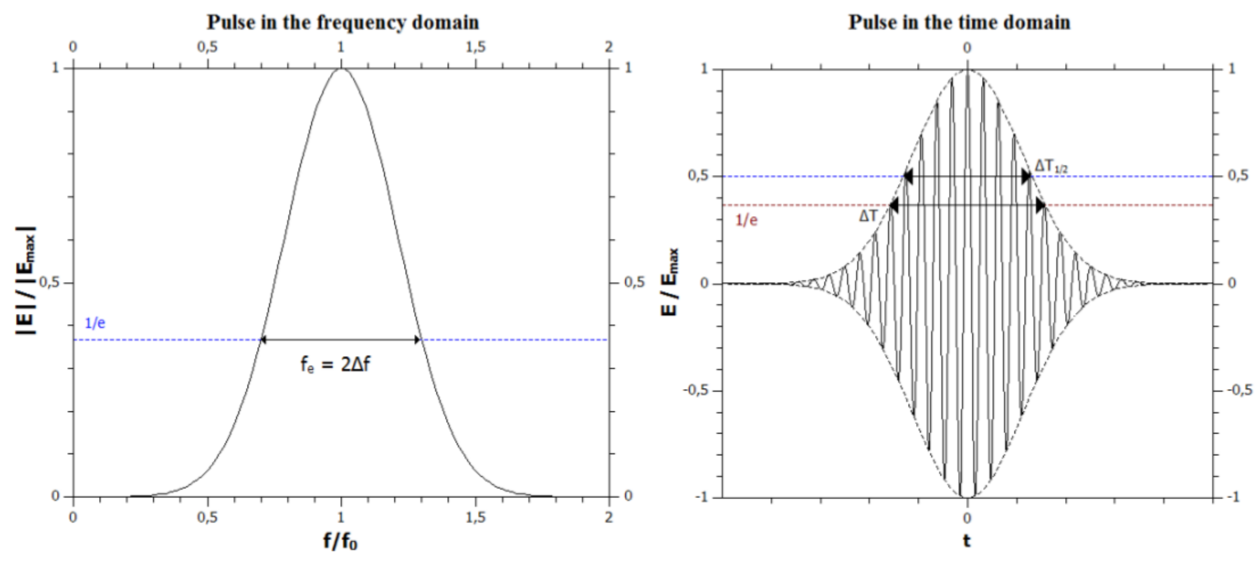
Overview

When ultrashort pulses are focused by an aplanatic lens, secondary maxima appear in the focal plane due to interference, analogous to the stationary (continuous wave) case. Through simulations, the effects of certain parameters like initial amplitude profile, numerical aperture, pulse length, and polarisation on the diffraction pattern in the focal plane can be examined.

Optical pulses

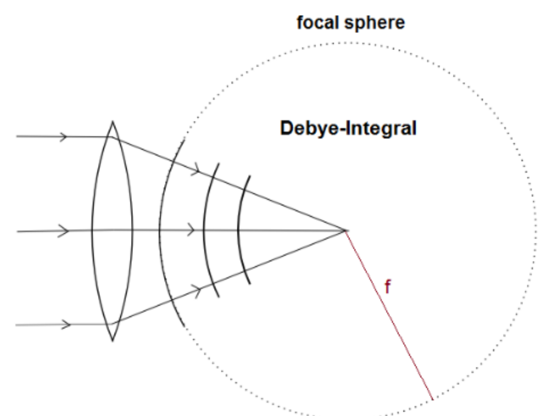
By assuming Gaussian-shaped pulses in the frequency domain, gaussian-shaped envelopes are obtained in the time domain [1]. This leads to the connection between pulse length $\Delta T_{1/2}$ and frequency width f_e: $\Delta T_{1/2} = \frac{1.06}{f_e}$



Schematic depiction of a gaussian-shaped pulse in the frequency domain (left) and in the time domain (right).

Simulation

The simulation is based on a vector-based Debye-Integral [2]. In the static case, a single light ray with its geometrical path is treated as a plane wave. Summing the resulting electric field vectors of a fixed number of plane waves gives the total electric field in the simulation plane. Polarisation effects can be factored in by applying a polarisation vector to every ray.

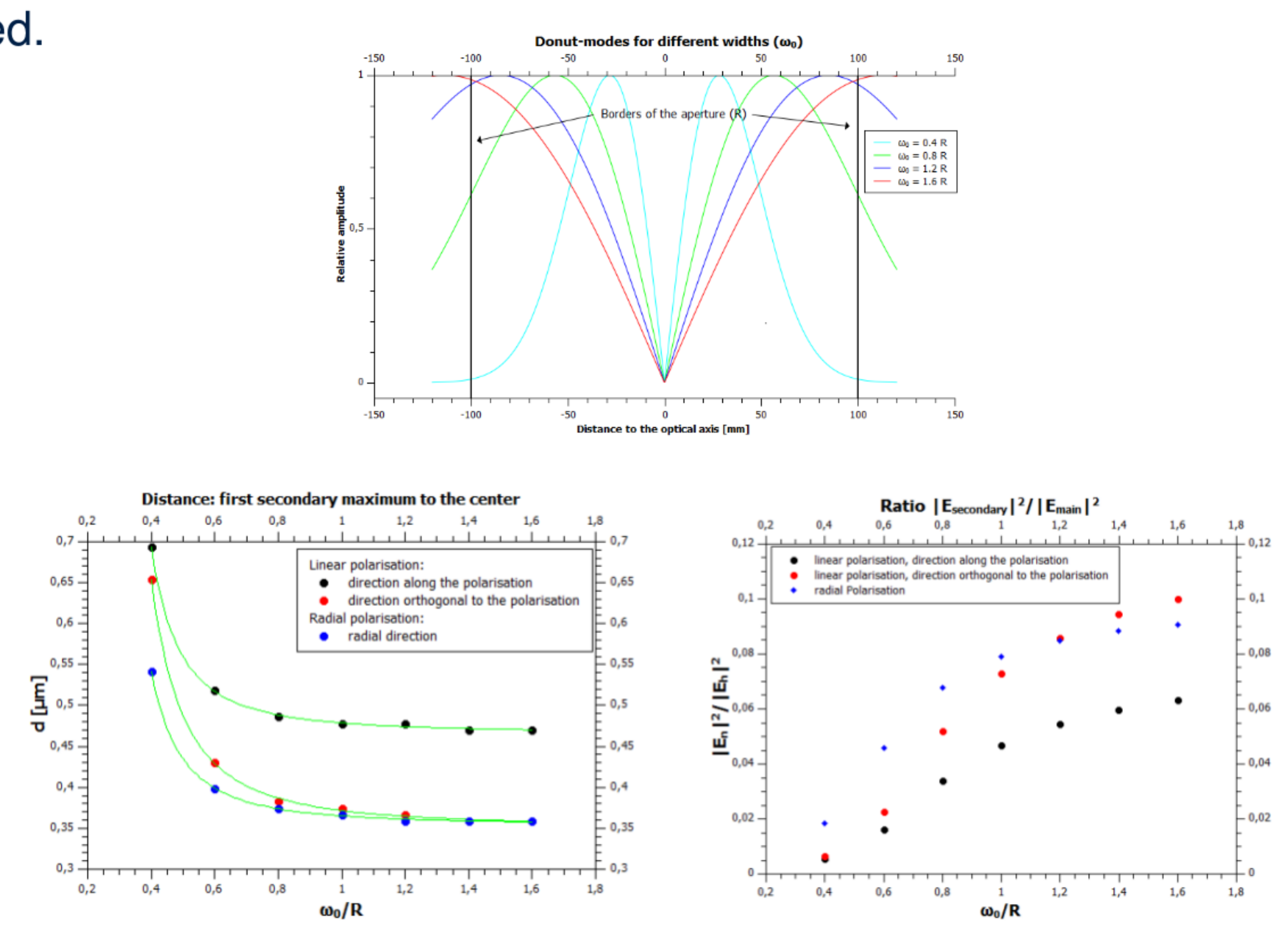


Debye-Simulation: superposition of plane waves propagating to the focus.

When dealing with pulses, the time-dependent field vectors of every frequency component in the focal area have to be summed up.

Initial amplitude profile

When dealing with radial-symmetric polarisations, the polarisation is undefined for rays propagating exactly along the optical axis. Therefore, it is necessary to use an initial amplitude profile where the electric field on the optical axis is zero. Here, the so-called Donut-mode was chosen: $A(r) = A_0 r \cdot \exp(-r^2/\omega_0^2)$. In the simulations of this box the stationary case with a numerical aperture (NA) of 0.9999 was considered.

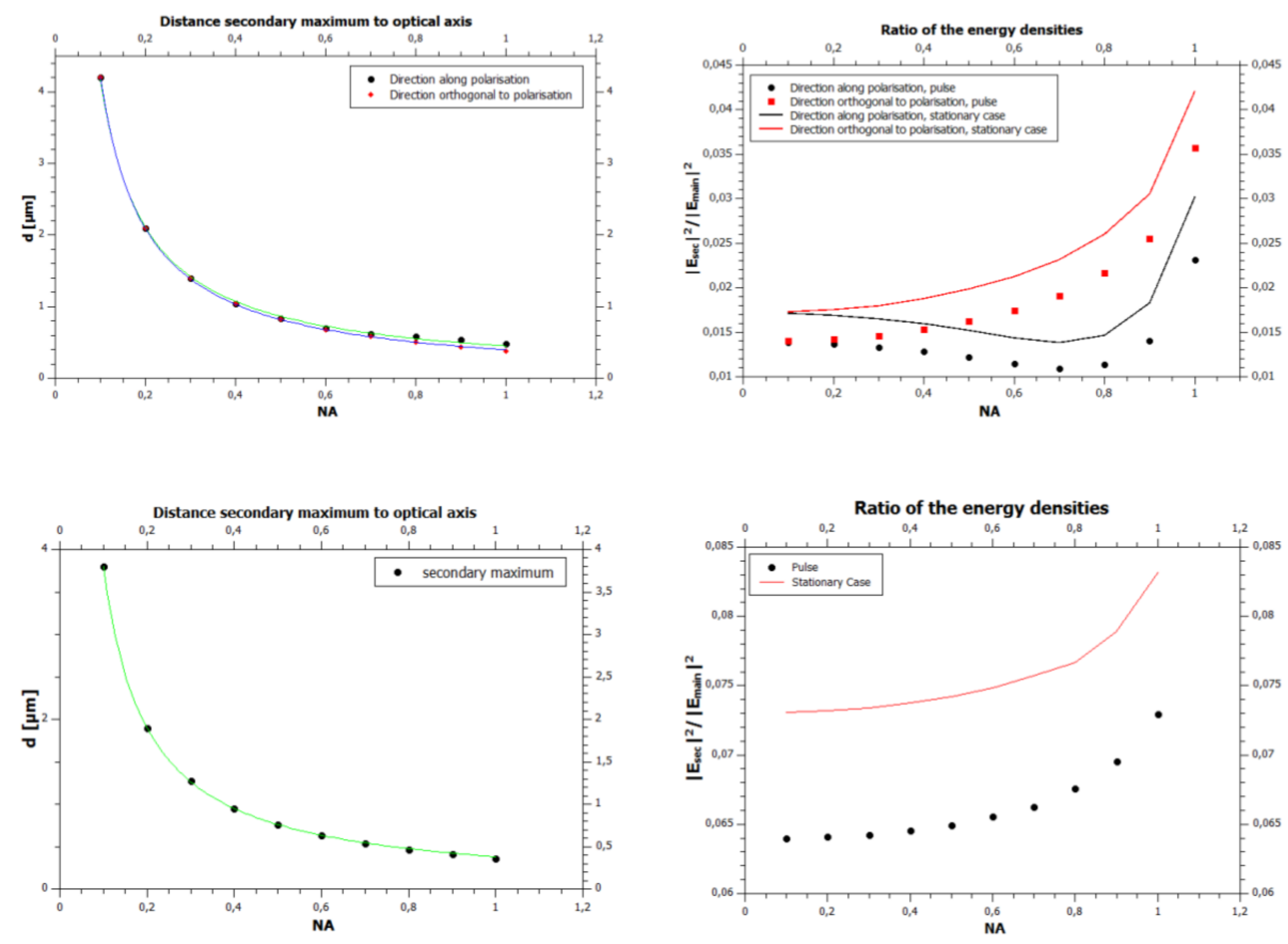


Depiction of Donut-modes with different widths (top), dependency of the distance between first secondary maximum and optical axis (bottom left) and relative energy density of the first secondary maximum (bottom right).

Here, both radial and linear polarisation are illuminated with a Donut-mode. However, when considering linear polarisation, the more common case of a homogeneous initial amplitude profile is examined in the following boxes instead.

Numerical aperture

The effects of varying the NA on the distance of the secondary maximum to the optical axis and its relative energy density for both radial and linear polarisation were examined. In these simulations, a pulse length of 7.07 fs was used.

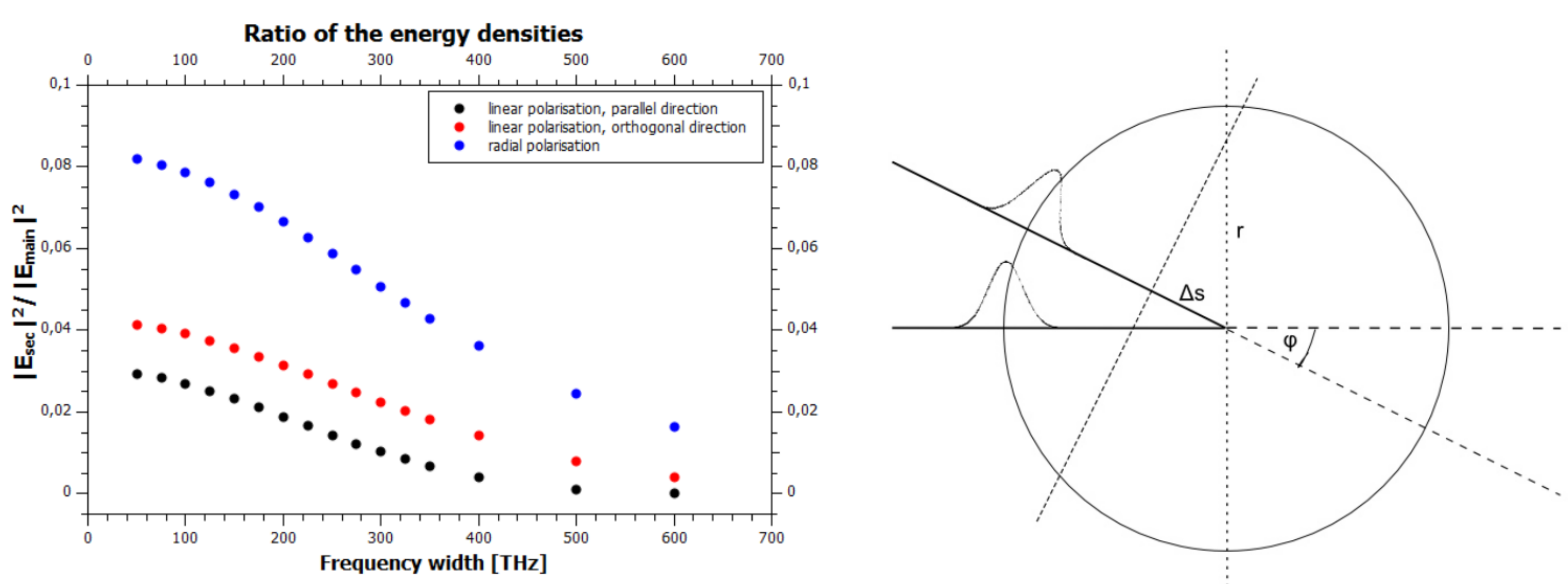


Distance between secondary maximum and optical axis and ratio of the energy densities for linear polarisation (upper row) and for radial polarisation (lower row).

An increase of the numerical aperture results in a decrease of the distance between secondary maximum and optical axis while the ratio of the energy densities increases drastically for NA $\geq$ 0.7.

Pulse length

Varying the pulse length does not change the distance between the secondary maximum and the optical axis. However, the ratio of the intensities between the secondary and primary maximum decreases steadily, as the pulses with plane wave fronts must be viewed at the same point in time, that is when their maxima are exactly at the focus. Then, in any non-axial point, the amplitudes for any sloped wave fronts are more and more suppressed the shorter the pulse is (see also figure on the right below). In these simulations, a NA of 0.9999 was used.



Ratio of the energy densities between the secondary and the primary maximum for linear and radial polarisations (left) and a schematic depiction of an incoming pulse in the focal sphere (right).

When further decreasing the pulse length, it becomes apparent that, for linear polarisation, the secondary maxima along the polarisation direction in the focal plane vanish.

In the orthogonal direction, a further decrease of the relative energy density can be observed. The same is true when dealing with radial polarisation. Therefore, it can be assumed that, in these cases, the secondary maxima also vanish asymptotically with even shorter pulse durations.

Conclusion

When studying the secondary maxima of light pulses focused by an aplanatic lens, two observations become apparent: Firstly, their distance from the optical axis and their relative intensity only depend on the numerical aperture of the lens, but are independent on the pulse length. Secondly, the ratio of the energy densities between secondary and primary maxima vanishes asymptotically for very short pulses.

[1] N. Lindlein, W. Iff, *Simulation of tightly focused ultrashort optical pulses taking into account polarization*, Proceeding (International Light Simulation Symposium (ILISIS), Nürnberg, 2012)

[2] P. Debye, *Das Verhalten von Lichtwellen in der Nähe eines Brennpunktes oder einers Brennlinie*, Article (Annalen der Physik 30, München, 1909)

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