Creation and Annihilation of Optical Phase Singularities

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Using a rigorous scattering model we study the electromagnetic field around a subwavelength slit in a metal plate with finite conductivity and finite thickness. It is found that the transmission can be strongly enhanced when the phase singularities ("optical vortices") of the Poynting vector field have a certain position. We examine the creation and annihilation of different kinds of phase singularities as a function of the incident wavelength and slit width.

The analysis of light transmission through a slit with a sub-wavelength width in a thin plate is a subject with a venerable history [1, 2, 3], dating back to Lord Rayleigh. Because of its importance for near-field optics and semiconductor technology, it continues to attract attention. Recently Ebbesen *et al.* observed extraordinary light transmission (i.e., more than 100%) through an array of sub-wavelength holes [4], which led to a new wave of interest in the subject. In this paper we study the light transmission through a single sub-wavelength slit in a metal plate of finite conductivity for the TE-polarization case. A rigorous computation of the field [5] demonstrates that for certain widths, there is an enhanced transmission through the slit. To understand this anomalous transmission, we have analysed the field of power flow (i.e. the time-averaged Poynting vector) near the slit. It is found that this field exhibits *optical vortices* and other kinds of *phase singularities* [6, 7], which are arranged in an array-like pattern. We find that the location and annihilation/creation of these phase singularities are intimately connected with the phenomenon of enhanced transmission.

A typical example of the calculations of the field of power flow near a slit is shown in Fig. 1, where the field is seen to exhibit phase singularities, i.e. points were the amplitude of the time-averaged Poynting vector is zero and as a consequence its direction, or equivalently its phase, is undetermined. It is seen that the anomalous transmission (namely $T = 1.11$) coincides with the presence of two optical vortices (a and b) *within* the plate, and a "funnel-like" power flow into the slit. This "funnel-like" effect corresponds to a transmission coefficient of more than one. In addition, four other phase singularities are visible just below the slit (c,d,e and f; two saddle points and two vortices). In Fig. 2 the location of the phase singularities is shown on a larger scale. It is seen that they are arranged in an array-like pattern. It is to be noted that only part of the phase singularities are shown—the pattern is continuous in a periodic way to the left and right, and also downwards.

Changing the slit width in a continuous manner causes the phase singularities to move through space. Near $w \approx 0.45\lambda$ the array of phase singularities along the symmetry-axis annihilate, each annihilation consisting of two vortices (one left-handed and one right-handed) and two saddle points. In Fig. 3 the resulting arrangement for $w = 0.5\lambda$ is shown. Because the annihilation of phase singularities leads to a smoother field of power flow,

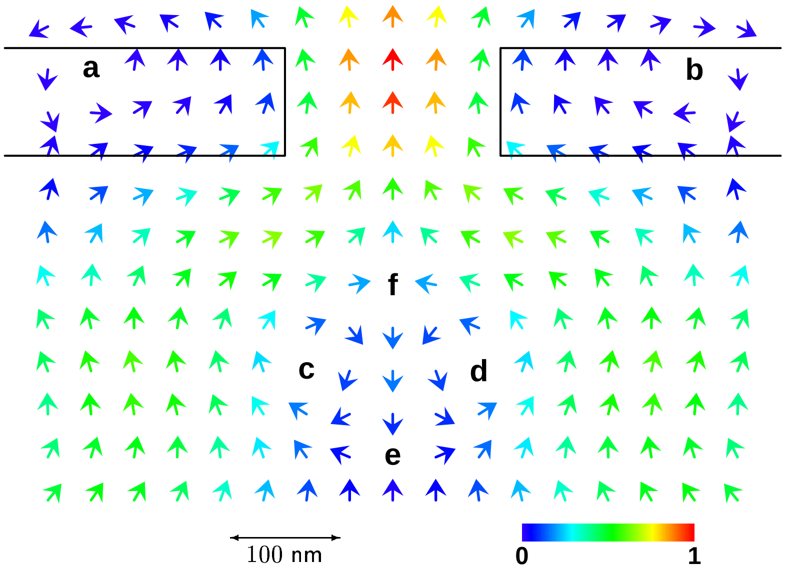

Figure 1: Behavior of the time-averaged Poynting vector near a 200 nm wide slit in a 100 nm thick silver plate. The incident light (coming from below) has a wavelength $\lambda = 500$ nm. The left-handed (a and e) and right-handed optical vortices (b and d) each have a topological charge of $+1$, whereas the topological charge of the saddle points (c and f) is -1. The transmission coefficient $T = 1.11$. The color coding indicates the modulus of the (normalized) Poynting vector (see legend).

an increased transmission is observed. Near other widths ($w \approx 1.4\lambda, 2.4\lambda, \ldots$) additional annihilations occur, each event corresponding with an increase in the transmission. In such processes the total topological charge is always conserved [8, 9].

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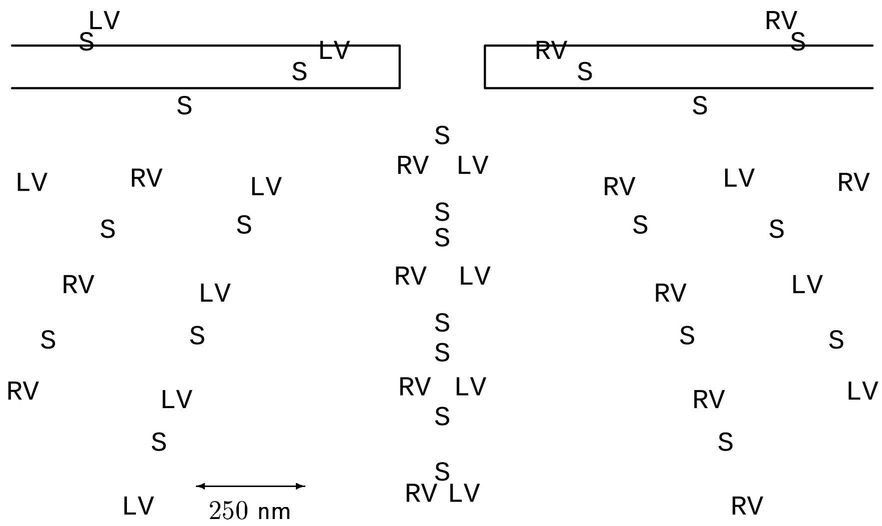

Figure 2: Location of phase singularities in the field of power flow near a 200 nm wide slit in a 100 nm thick silver plate. The incident light (coming from below) has a wavelength $\lambda = 500$ nm. The left- and right-handed optical vortices are denoted by lv and rv, respectively. s denotes a saddle point.

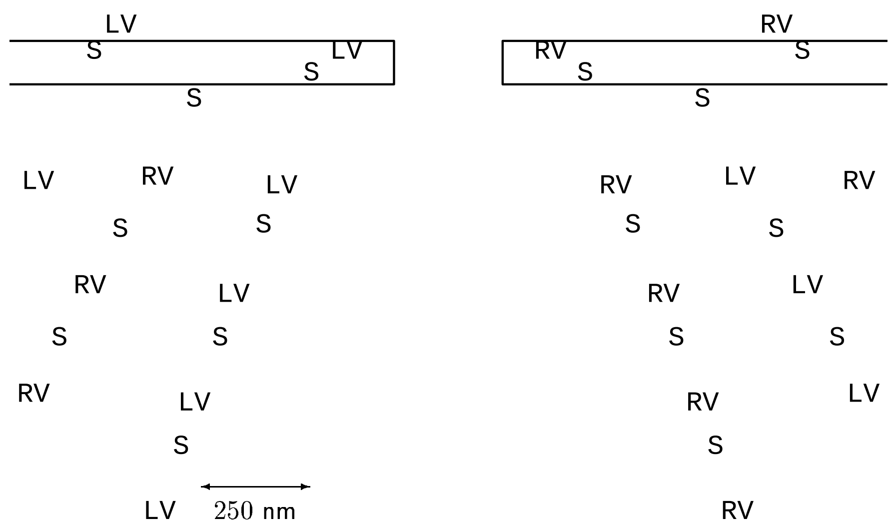

Figure 3: Location of phase singularities in the field of power flow for the same configuration as in Fig. 2, but now for a slit width $w = 250$ nm. Notice that the central array of phase singularities visible below the slit in Fig. 2 has now been annihilated.