UNIVERSITY OF PÉCS

Doctoral School in Physics
"Laser and Plasma Physics, Laser Applications" Program

Theses of the Dissertation

Scattering of ultrashort light pulses on subwavelength nanoslits

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1. Theoretical overview

Light transmission through small apertures is a classical problem of the diffraction theory, one of the most important results of optics. It was Rayleigh who showed that two objects may be resolved if the main maximum of one of the patterns coincides with the (first) minimum of the other pattern. In 1928 Synge introduced the principle of near field optics. According to this principle, by using a sufficiently small (subwavelength-size) slit the resolution limit of optical microscopy determined by Rayleigh can be overcome. The problem of light transmission through subwavelength apertures formed in perfect conductor metal screen was treated by Bethe in 1944 and by Levine and Schwinger by 1948. The idea of Synge was realised by Lewis *et al.* and Pohl *et al.* in 1984.

In the last decade the scattering of light on nanostructured optical elements became one of the most investigated fields of research. Perhaps the most interesting feature of the scattering of light on such subwavelength metallic objects is resonant enhancement. This phenomenon was first demonstrated by Ebbesen *et al.* in a periodic grating of subwavelength apertures. The origin of the enhancement is still debated: some theories associate it with surface plasmon resonances, others with intraslit waveguide mode resonances.

The theories modeling the transmission of ultrashort (terahertz, femtosecond) pulses through nanostructures are also of high importance. Many physical processes —such as the vibrational motion of molecules or the carrier redistribution in the band structure of semiconductors— observed in condensed matters and molecules occur on the picosecond or femtosecond time scale. In most femtosecond-resolved experiments the information is averaged in space. This averaging is particularly annoying when the process is examined in nanostructured materials; therefore the development of techniques with femtosecond-scale temporal and nanometer-scale spatial resolution is particularly important.

2. Objectives

The previous researches primarily dealt with the electromagnetic field behind the slit and the effect of the transmission coefficient of the slit on a continuous light wave. However, the fields in front of and inside the slit were

investigated only by a few studies. Moreover, there are only a few known analytical formulae describing this problem. The analytical formula that is commonly accepted in the literature (developed by Takakura) describing the transmission through a single slit, in contrast to the transmission enhancement demonstrated in the literature, indicates attenuation.
Another interesting problem that has been, up till now, treated primarily experimentally in the literature is the transmission of ultrashort pulses through apertures. The questions "How the transmission of ultrashort pulses through nanoapertures modifies the spatial and spectral shape and length of the pulse?" and "Which parameters of the slit and the pulse affects the shape of the transmitted pulse?" are still not clarified.

The objectives of the dissertation are the followings:

1. The examination of the electromagnetic fields of a continuous light wave transmitted through a single subwavelength nanoslit in front of and inside the slit. Finding formulae that describe these fields. Determination and examination of the reflection coefficient.

2. Determination of analytical formulae describing the electromagnetic fields in front of and inside the slit and the transmission coefficient. Comparison with the analytical and numerical formulae described earlier in the literature.

3. Development of a model describing the transmission of ultrashort pulses through subwavelength nanoslits. Examination of the enhanced transmission and spatial localization of the pulses and the modifications observed in the field around the slit caused by the temporal profile of the pulse.

3. Methods

In the dissertation formulae for the electromagnetic fields around the slit are determined starting from the numerical method of Betzig *et al.* based on the Neerhoff and Mur-solution of Maxwell's equations. The original formalism describes the diffraction of a TM-polarized continuous light wave transmitted through a slit of width $2a$ that is cut parallel to the y axis into a screen with thickness b. The solution uses the two-dimensional Green's theorem, using different Green's functions in the three regions (in front of, inside, and behind the slit). In this way four integral equations can be determined that can be solved numerically.

In Chapter 5, formulae are given for the fields in front of and inside the slit that follows (but are missing) from the paper of Betzig *et al.* With these formulae local definition may be found for the reflection coefficient.

In Chapter 6, numerical formulae are determined for the electromagnetic fields in front of and behind the slit that are valid for distances $z \gg 2a$. This follows from the numerical method in which the slit is divided to N subintervals; for the number N, the inequality $N > 2a/z$ must be true. This means that $z > 2a/N$ also holds. Therefore, by dividing the slit to one subinterval, we receive the expression above. With this expression, simple analytical formulae may be determined in region I (in front of the slit) and III (behind the slit). These formulae give correct values for the location and the magnitude of the transmission resonances.

Finally, based on the formulae describing the transmission of continuous waves through a single subwavelength nanoslit, in Chapter 7 the components of the electromagnetic field of an ultrashort pulse transmitted through a single slit are determined. This was performed using the fast Fourier-transform.

The calculations were performed with different versions of the mathematical program packages *Maple* and *Mathcad*; we also used specialized programs written in the programming languages *Fortran 77* and *Pascal* (Delphi). While the former mathematical packages use built-in algorithms that may not be optimal for the given problem, using the latter programming languages it is possible to create optimized algorithms leading to programs that are running much faster.

4. Theses

Below I summarize the new results presented in the dissertation.

1. I determined the R reflection coefficient and the electric and magnetic fields of a continuous wave (Fourier-component of a wavepacket) passing through a nanometer-size slit in front of and inside a slit of width smaller than the wavelength cut into a screen of thickness smaller than the wavelength. I showed that the main reflection resonances appear with $\lambda/2$ periodicity at screen thicknesses that are smaller than the thicknesses that belong to the transmission resonances; at the transmission

resonances the function $R(b)$ has minima. I also showed that the intraslit energy flux can be one order of magnitude larger than the energy flux in front of or behind the slit. I confirmed with numerical calculations that the enhanced transmission and the enhancement of the field in front of the slit can be attributed primarily to the resonant excitation of the Fabry–Pérot-like electromagnetic field inside the slit. [S5,S6]

2. I determined analytical formulae for the fields in front of and behind the slit. Comparison of the results obtained by using these formulae with the results of the rigorous numerical formulae and the semianalytical model that describes the field in the first region (in front of the slit) as the interference of the incident and reflected waves I showed that the location and the shift of the transmission resonances are described exactly by either of the three models; however, while the latter semianalytical model predicts transmission attenuation, the other two models indicates enhancement. [S4]

3. I developed a numerical model describing the transmission of ultrashort pulses through subwavelength nanoslits that is based on the numerical model for continuous waves. [S1,S2,S3] I showed that in the near zone ($|z| \approx 0.1a$) the pulse experiences deformation owing to the effect of the slit edges, while in the far zone ($|z| \approx 10a$) the pulse exhibits semicircular field distribution; the pulse with the smallest deformation can be observed at $|z| \approx a$. [S3]

4. I verified with numerical calculations that it is possible to produce nanometer-scale spatial and femtosecond-scale temporal optical resolution with the diffraction of ultrashort light pulses on subwavelength nanoslits. [S1,S2,S6] I showed that the transmission of the pulse without temporal broadening is limited by the transmission characteristics of the slit. With the examination of the $T(a, b, \lambda)$ transmission coefficient at different parameters I showed that the shape and enhancement of the transmitted pulse is determined by the relation of the pulse length and the transmission function. [S2] In the case of short pulses I showed by examining the frequency components of the pulse far from the central frequency that these components experiment a different enhancement than the central frequency, leading to pulse broadening and smaller enhancement. [S2,S6]

5. I showed that while in the case of continuous waves the near field zones in front of and behind the slit are very much alike owing to the symmetry of the slit [S5], in the case of ultrashort pulses the electromagnetic field in front of the slit produced by the incident, reflected and diffracted fields may differ significantly from the field behind the slit, resulting in an easily distinguishable zero-level in the first region. I verified that in the case of pulses, similarly to the continuous wave case, the energy flux of the intraslit field is a few times larger than the energy flux of either the field in front of or behind the slit. The ratio is determined by the pulse length and the transmission characteristics resulting from the slit geometry. By examining the temporal field distribution along the z axis, in the case of ultrashort pulses I found three enhancement regions (stationary, quasistationary, and nonstationary) that can be characterized by pulses of different lengths

5. Publications

Related publications

[S1] S.V. Kukhlevsky, M. Mechler, L. Csapo, K. Janssens. *Near-field diffraction of fs and sub-fs pulses: super-resolution of NSOM in space and time*. Phys. Lett. A, **319**:439-447, December 2003.

[S2] S.V. Kukhlevsky, M. Mechler, L. Csapo, K. Janssens, O. Samek. *Enhanced transmission versus localization of a light pulse by a subwavelength metal slit*. Phys. Rev. B, **70**:195428, November 2004.

[S3] S.V. Kukhlevsky, M. Mechler. *Detailed structure of femtosecond and sub-femtosecond pulses diffracted by a nanometre-sized aperture*. J. Opt. A: Pure Appl. Opt., **5**:256-262, May 2003.

[S4] S.V. Kukhlevsky, M. Mechler, O. Samek, K. Janssens. *Analytical model of the enhanced light transmission through subwavelength metal slits: Green's function formalism versus Rayleigh's expansion*. Appl. Phys. B, **84**:19-24, July 2006.

[S5] S.V. Kukhlevsky, M. Mechler, L. Csapó, K. Janssens, O. Samek. *Resonant backward scattering of light by a subwavelength metallic slit with two open sides*. Phys. Rev. B, **72**:165421, October 2005.

[S6] M. Mechler, O. Samek, S.V. Kukhlevsky. *Enhanced transmission and reflection of few-cycle pulses by a single slit*. Phys. Rev. Lett., **98**:163901,

April 2007.

Conferences

[K1] M. Mechler, S.V. Kukhlevsky. *Anomalous backward scattering of light by a two-side-open subwavelength metallic slit.* In: Device and Process Technologies for Microelectronics, MEMS, and Photonics IV, Proceedings of SPIE. Eds.: J.-C. Chiao, A.S. Dzurak, C. Jagadish, D.V. Thiel 6037, 2005.

[K2] S.V. Kukhlevsky, M. Mechler, L. Csapo, K. Janssens, O. Samek. *Non-diffractive subwavelength beam nano-optics.* In: The International symposium on optical science and technology. Plasmonics: metallic nanostructures and their optical properties. 2. SPIE 5512-21. / N.J. Halas, T.R. Huser. - Denver, Col. : SPIE, 2004. - 37.

[K3] M. Mechler, L. Csapó, S.V. Kukhlevsky. *Enhanced transmission and localization of light at a nanometer-size metallic slit on the femtosecond time scale.* Conference of ESF Femtochemistry & Femtobiology (Ultra) Program, (2004)

Other publications

1. S.V. Kukhlevsky, M. Mechler. *Diffraction-free subwavelength-beam optics at nanometer scale* Opt. Commun., **231**:35-43, February 2004.
2. O. Gühne, M. Mechler, G. Tóth, P. Ádám. *Entanglement criteria based on local uncertainty relations are strictly stronger than the computable cross norm criterion.* Phys. Rev. A (Rapid Communication), **74**:010301(R), July 2006.