Summary of a PhD work

APPLICATIONS OF A GAUSSIAN LIGHT BEAM TO DESIGN OF FEMTOSECOND LASERS AND TO DESCRIPTION OF CROSS-POLARIZATION EFFECTS

AMBRUS KŐHÁZI-KIS

Kecskemét College, Faculty of Mechanical Engineering and Automation
Department of Mathematics and Physics
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I. PRELIMINARIES AND GOALS

The dissertation is divided to three main parts. In the first part I investigate reflection of ultrashort light pulses (A). In the second part I deal with description and design of resonators of Kerr-lens mode-locked Ti:sapphire lasers (B). In the third part I investigate cross-polarization effects of focused light beams using the three-dimensional model of light beams (C).

(A) One of the main trends of laser physics nowadays is the research and development of femtosecond laser sources. In the operation of femtosecond lasers, of amplifiers or of any other optical systems connected to femtosecond light pulses the reflection of a few femtosecond long light pulses is critical. The spectral range of reflection has to be broad enough and the group-delay dispersion has to be free of resonances within this spectral range.

The phase-modulated dielectric mirrors (invented in 1993) promised good parameters for these purposes. I worked with Róbert Szipőcs (one of the owners of the patent of the phase-modulated mirrors) on clarifying the working principles of phase modulated dielectric mirrors. My first goal was to investigate the relation between the working principle of phase modulated mirrors and of the holography in the time domain. My second goal was to construct a time-domain hologram that is usable to reflect femtosecond light pulses effectively.

(B) Longitudinally pumped Kerr-lens mode locked Ti:sapphire lasers are used in most laboratories to generate femtosecond light pulses. These lasers can be pumped by Ar-ion gas lasers, or by intracavity frequency doubled Nd lasers. Purchasing and running these pump light sources are quite expensive, their cost strongly limits possible applications of Ti:sapphire femtosecond lasers.

I investigated the operational principles of longitudinally pumped Kerr-lens mode-locked Ti:sapphire lasers, especially the laser resonator. My aim was to construct a realistic model of the lasers in order to use it for designing laser resonators that need as low pump power as possible, and provide as high Kerr-lens sensitivity as possible.

(C) The polarizational properties of focused light beams can play an important role in optical data storage, in micromachining or in microscopy. Two-dimensional (2D) description of polarizational states of focused light beams is widely used. The three-dimensional (3D) description that takes into account the longitudinal electromegnatic field also yields usually only small perturbation to the electromagnetic field distribution determined by the 2D model. As the light beam is focused more strongly the cross-polarizational effects (polarizational effects that follows from the 3D model but does not follow from the 2D model) become more significant.

Though the 3D description of focused light beams has been known for a long time, the problem of cross-polarization effects is, however, still not settled experimentally and thus remains controversial theoretically. My aim was to investigate the polarizational properties of focused light beams, and to demonstrate cross-polarization phenomena.

II. METHODS OF INVESTIGATION

In my work I applied theoretical as well as experimental methods.

The model of Gaussian light beams play a central role in my dissertation. Calculating the propagation of Gaussian light beams, or the Fresnel-Kirchoff integral I used the so called Siegman-lemma:

$$\int_{-\infty}^{\infty} \exp\left(-a\,t^2 - 2\,b\,t\right) dt = \sqrt{\frac{\pi}{a}}\,\exp\left(\frac{b^2}{a}\right)$$

This integral yields finite value if the real part of *a* is positive: $\mathrm{Re}(a) > 0$.

Using Gaussian approximation for the temporal shape of the ultrashort light pulses I could obtain simple, easy to eavaluate formulas in the description of the interference of phase-modulated light pulses. The Gaussian approxiamtion was used also for the temporal and spatial distribution of the light pulses in describing spectral decomposition of ultrashort light pulses and in describing the interference of spectrally resolved pulses in the spectrally resolved holography.

To describe the saturation of the gain of the Ti:sapphire laser crystal I applied atomic rate equations.

In description of Kerr-lens mode-locked Ti:sapphire laser resonators I utilized the fact that working in their preferred mode these lasers yield almost perfect fundamental mode Gaussian light beams: I used the well known generalized ABCD matrix technics to model the propagation of light beam within the laser resonator. I used different ABCD matrices for the optical elements in the saggital and in the meridional plane to describe propagation of a light beam through the astigmatic optical elements of the astigmatically compensated laser resonator. I applied different ABCD matrices in the saggital and in the meridional planes for description of the optical Kerr-lens effect of the astigmatic light beams. The thermal lens effect and the gain-guiding effect were described using the paraxial approximation of light beams.

I wrote computer programs in Pascal and C++ programming language based on my theoretical model. The steady state light beam parameters had to be determined using successive approximation because of the nonlinear effects resulting from the Kerr-lens effect, from the saturation of the depletion of the pump beam and from the saturation of the gain of the generated beam. I optimized the parameters of the laser resonators using the Nelder-Mead optimizing algorithm. This is a well known search algorithm for local optimum, but starting it from random parameter values it can find global optimum also.

I built the designed lasers in the laboratories of the Department of Laser Appliocations of the Research Institute of Solid State Physics in Budapest. The Ti:sapphire laser crystal was pumped by an Ar-ion laser produced by Spectra-Physics.

I used Gaussian approximation for the description of the cross-polarization effects also. The theoretically predicted cross-polarization effect was demonstrated by using a He-Ne laser and simple film polarizers. The transversal shape of the cross-polarized light beam was recorded by a CCD camera produced by DVT company.

III. RESULTS

1. I investigated the relation between the Fourier-synthesis [T1] of the phase-modulated dielektric mirrors and the operating principle of temporal holography. I have developed a theoretical model [T2] that supports the understanding of the phase-modulated behaviour, and form the basis for the Fourier-transform method of the synthesis of dispersive dielectric mirrors.

2. I investigated spectrally resolved interference phenomena of temporally and spatially Gaussian light pulses. The simply formulas obtained from the Gaussian model were used to determine optimal experimental parameters for spectrally resolved holography experiments [P1].

3. I investigated the saturation of the gain of a longitudinally pumped Ti:sapphire laser crystal. I showed that calculating the saturation of the gain we have to take into account not only the saturation caused by the generated beam but the saturation caused by the pump beam also:

$$g = N\,\sigma_L \frac{p}{1+s+p},$$

here g is the saturated gain coefficient, N is the concentration of the Ti-ions, σ_L is the Ti-ions' gain cross-section, furthermore s and p are the relative intensity parameters of the generated and the pump beam [P2].

4. I constructed the theoretical model of Kerr-lens mode-locked femtosecond Ti:sapphire laser resonators, in which besides of the Kerr-lens effect I took into account the saturation of the gain, the gain-guiding effect, the thermal lens effect, the gain depletion caused by the increased temperature in the laser crystal also. I wrote a computer program based on my theoretical model. I used this program to design resonators of Kerr-lens mode-locked lasers. I designed and built low pump power threshold [P4] and high output power [P2] femtosecond Ti:sapphire lasers. Based on these lasers we constructed a new type femtosecond light sources [T3,T4,P3], that produce femtosecond light pulses which are synchronized, but they have different spectra.

5. I have shown that the cross-polarization effects occur whenever the reflection or the transmission coefficients depend on the polarizational state of the incident light. I have shown that if the incident light beam is a fundamental Gaussian beam then the cross-polarized light component is always a first-order Hermite-Gaussian light beam in the paraxial approximation. [T5]

6. I have gibven a description of the cross-polarization effect that occurs when a fundamental Gaussian light beam polarized in the plane of incidence falls on an isotropic dielektric plane surface at Brewster's angle. I experimentally demostrated that the reflected beam showed the theoretically predicted behaviour. I proposed a new, experimentally very simple method to generate radially polarized light beams [T5].

IV. REFERENCES

Refereed articles:

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Design of dielectric high reflectors for dispersion control in femtosecond lasers

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T2. R. Szipőcs, A. Kőházi-Kis:

Theory and design of chirped dielectric laser mirrors

Appl. Phys. B 65 (1997) pp. 115-135

T3. R. Szipőcs, E. Finger, A. Euteneuer, M. Hofmann, A. Kőházi-Kis:

Multicolor, mode-locked Ti:sapphire laser with zero pulse jitter

Laser Physics 10 (2000) pp. 454-457

T4. R. Szipőcs, A. Kőházi-Kis, P. Apai, E. Finger, A. Euteneuer, M. Hofmann:

Spectral filtering of femtosecond laser pulses by interference filters

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T5. A. Kőházi-Kis:

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Advanced Solid-State Photonics Conference, Vienna, Austria, WB17 (2005).