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Introduction

In this thesis, partially coherent laser beams are described using the Wigner distribution. The measurement of the Wigner distributions of an aberrated helium neon laser and a tapered semiconductor laser are presented.

1.1 Motivation

The starting point of this thesis is the necessity to characterize the output of high-power semiconductor lasers within the MDS ("Modulare Diodenlaser Strahlwerkzeuge" - Modular Semiconductor Laser Tools) project[1].
Semiconductor lasers have a very good electrical-to-optical efficiency. A main advantage in comparison to CO_2 lasers, the only other type of laser with a similar efficiency, is the ability to guide their output in fiber waveguides. The aim of the MDS project was to build improved diode laser systems and to use them to anneal, solder, cut, and weld metals. These are applications in the field of mechanical engineering and in the automotive industry commonly done by CO_2 or solid state lasers. The drawback of a semiconductor laser is its low output power. A single semiconductor laser achieves a stable output of up to 5 W. In order to obtain powers in the kW range, the outputs of many semiconductor lasers have to be combined.
The key attributes of a complete laser system are the beam power and the beam power per area on the workpiece that can be achieved by a focussing system of specified numerical aperture. As the numerical aperture of the focussing system defines the convergence angle of beam, the figure of merit connected to

[1]The results of this project will be published by Springer-Verlag this year.

the second attribute is the beam power per volume in spatial-angular-space, called the beam brightness. The geometrical combination of several beams intends to place them next to each other in spatial-angular-space. In this way, the beam power and the volume in spatial-angular-space are increased. However, the beam brightness can not be improved by this technique.
In order to enhance the beam brightness of the complete laser system, the brightness of the elementary semiconductor lasers has to be increased. This can be done by lateral shaping of the semiconductor. Using a tapered structure, a very high beam brightness can be achieved [Wal96]. Within the MDS project, Mikulla and Kelemen of the “Institut für Angewandte Festkörperphysik”[2] produced the first tapered semiconductor lasers.

1.2 Laser Beam Description

The Maxwell equations are a set of time and space dependent vector equations for the electric field, $\vec{\mathcal{E}}$, and magnetic field, $\vec{\mathcal{B}}$. It is laborious to apply them directly to laser beam propagation. In addition, neither the electric nor the magnetic field vector of an optical beam can be measured directly. To a good approximation, a laser beam can be described by its wavelength, its state of polarization, its power density distribution, its wavefront, and its coherence properties:

$$\vec{\mathcal{E}} \left\{ \begin{array}{l} \text{wavelength, } \lambda \\ \text{polarization} \\ \left.\begin{array}{l} \text{power density, } E \\ \text{wavefront, } W \\ \text{cohrence, } \kappa \end{array}\right\} \begin{array}{l} \text{Wigner distribution, } \mathit{WD} \\ \text{mutual coherence, } \Gamma \end{array} \end{array}\right.$$

All laser systems used in this thesis are linearly polarized. Measurements of the wavelength and the polarization are not discussed in this thesis. The power density, the wavefront, and the coherence properties of a beam are time average properties. They are connected to each other. Their propagation can only be predicted if all three of them are known. They can be described by the Wigner distribution, WD, or the mutual coherence, Γ. WD and Γ are connected to each other by a Fourier transform. The emphasis of this thesis lies on the Wigner distribution for the following reasons: The Wigner distribution can be intuitively interpreted as a density in spatial-angular-space [Bas78]. Therefore, the brightness of a beam, discussed above, can be directly obtained from the

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extension of its Wigner distribution. The Wigner distribution is connected to the power density distributions a beam takes as it propagates via a Radon transform [Epp95]. This can be used in the reconstruction of the Wigner distribution of a beam from measured power density profiles. Finally, in contrast to the mutual coherence, the Wigner distribution only takes real values.

An alternative approach is the measurement of the mutual coherence from the interference of one part of the beam with another. The drawback of an interference setup is its sensitivity to environmental influences. In addition, these systems are restricted to comparatively coherent beams. One has to note that although interferometers are commonly used to determine the wavefront distortion introduced by optical systems [Mal92] their application on laser beams is not very common[3].

Thus the "Wigner analysis" of the power density profiles of a laser beam is a promising new technique that enables the analysis of the wavefront and coherent properties of a laser beam on the basis of standard power density measurements. The method to reconstruct the Wigner distribution from the measured data is comparatively new. It has to be tested using a well known beam. Eppich investigated mixtures of Hermite-Gaussian beams [Epp01b]. His measured coherent properties show a good agreement with the results of an interferometric measurement.

This thesis focuses on the wavefront properties of a laser beam. The propagation of the Wigner distribution through an arbitrary optical system can be found in the work by Bastiaans [Bas78]. However, his discussion is brief. Most publications that followed use an approximation formula for the calculation the Wigner distribution behind an aberrated optical system. In this thesis, the impact of an non-ideal optical system on the Wigner distribution is discussed in some detail. The formalisms of wave aberration and of the Wigner distribution are expressed in terms commonly used in the field of experimental laser physics.

1.3 Layout of this Thesis

The following chapter outlines the theoretical description of laser beam propagation. The emphasis lies on the approximations made in the Maxwell equations for the description of a partially coherent beam using the mutual coherence (sections 2.1 to 2.3). In section 2.4, the concept of the wavefront of a beam is introduced.

[3] The idea to introduce an international standard of the interferometric measurement of the wavefront of a laser beam was abandoned due to lack of interest.

In section 3.1, the Wigner distribution is defined as the Fourier transform of the mutual coherence. In section 3.2, the second order moments of the Wigner distribution are used to calculate the widths of the beam in spatial-angular-space. The base of the algorithm, used to reconstruct the Wigner distribution from measurement data, is given in section 3.3.
In chapter 4, the description of non-ideal optical systems is discussed (sections 4.1 and 4.2). The impact of a beam aberration on the volume in spatial-angular-space, which a Wigner distribution occupies, is analyzed in some detail in section A.3. The results of numerical calculations, which closely resemble the experimental situation of section 5.2, are presented in section 4.4.
In section 5.1, the steps of the measurement and data evaluation are detailed. Several experiments using the output of a helium neon laser, which is aberrated in a well defined manner, are reported in sections 5.3 to 5.5.
In chapter 6, the experimental results obtained from the measurement of a tapered semiconductor from the "Institut für Angewandte Festkörperphysik" are reported.
Chapter 7 presents the conclusions reached from the analysis of the experimental results and provides some speculations towards future work necessary to improve of the use of the Wigner distribution for the analysis of experimental results.
The formulas required for the evaluation of the measured Wigner distribution are summarized in the appendix.

Equations that are of paramount importance in the numerical investigations and the evaluation process of measured data are highlighted by a gray box.