Fundamental Methods to Measure the Orbital Angular Momentum of Light

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CHAPTER 1

Introduction

Light is a ubiquitous carrier of information. Its intensity, direction, frequency and polarisation provide knowledge about its source and the medium it has propagated through. By means of photodetectors, cameras, spectrometers and polarisers, these properties of light can be measured efficiently. Not only can one obtain knowledge about the source and medium in this way; one can also use light to transfer data from one place to another by encoding this data in one or more properties of the light.

In the past twenty years, great interest has been shown for another property of light, its orbital angular momentum. Contrary to the polarisation, which is associated with the spin angular momentum of light and can take two orthogonal states, the orbital angular momentum can take infinitely many orthogonal states. If this property can be measured efficiently, it opens the way to interesting new physics and could serve as an additional property to encode data in, with its infinitely many possible states as its greatest asset.

The orbital angular momentum of light is associated with Laguerre-Gaussian beams, that contain a phase singularity around which the phase of the field increases in an azimuthal fashion, $\exp(i\ell\phi)$, forming a so-called optical vortex. The intensity vanishes at the position of the singularity, forming a dark hole in the intensity profile of the beam. Each photon in a Laguerre-Gaussian beam carries an orbital angular momentum of $\ell\hbar$. ℓ is often also used to indicate the topological charge of the optical vortex. The case where $\ell = 0$ corresponds to a flat wave front, of which the light coming from a distant point source, for instance a star, is the most common example. Generating beams with an optical vortex is accomplished by special optical elements, such as a spiral phase plate, a fork hologram or a spatial light modulator, that all imprint the azimuthal phase profile to an incoming beam. A wide range of ℓ can be achieved in this way. Optical vortices also occur naturally, for example as higher-order laser modes, in speckle patterns and in optical caustics.

Efficient measurement of the orbital angular momentum of light is very challenging. An ideal measurement system should have infinitely many output ports, each corresponding to a different orbital angular momentum state, much like a polarising beam splitter for measuring the spin angular momentum, which has two output ports, corresponding to each of the two polarisation states. An alternative way to determine the spin angular momentum of a photon is to use a polariser, which transmits one of the states and blocks the other and can be seen as a filter for a specific spin angular momentum state.

Several methods to measure the orbital angular momentum of light have been studied in the past. Interference of a beam containing an optical vortex with a flat wave front results in an interference pattern with a fork-like structure that reveals the topological charge of the vortex. The need for an additional flat wave front make this method unfavourable for many applications, especially when the beam under study is spread out over a large area. A filter for orbital angular momentum states can be achieved with a spiral phase plate, that can be used to test whether the input light is in a specific state or not. Finally, a system of Mach-Zehnder interferometers and Dove prisms provides a measurement of the orbital angular momentum state, but is technically very challenging and difficult to implement in a larger optical system.

In this thesis, we present two new ways to measure the orbital angular momentum of light. The first method, which we describe in detail in chapter 2 and 3, is based on a multi-pinhole interferometer, a system of a number of pinholes arranged on a circle. We demonstrate that by studying the diffraction pattern behind such a multi-pinhole interferometer, one can determine the topological charge of an incoming optical vortex. Since a multi-pinhole interferometer consists of a finite number of apertures, that can be placed far apart, this system can be used to study optical fields with large-scale intensity fluctuations, such as, for instance, can be expected in astronomy. The multi-pinhole interferometer can also be used to make optical vortex maps of an optical field, which makes it possible to not only determine the topological charge of the vortices in the field, but also their anisotropy and orientation. We describe this method and present its results for a speckle pattern in 4 and 5.

In chapter 6, we present the second new way to measure the orbital angular momentum of light, the mode sorter, which approaches the ideal measurement system described before very closely. The mode sorter consists of two custom optical components that transform the azimuthal phase profile of an optical vortex into a tilted plane wave. An additional lens focusses these tilted plane waves to different positions on a detector. These positions are related to the orbital angular momentum of the incoming light. In chapter 7 we demonstrate that this mode sorter can also determine the contribution of each orbital angular momentum state in a superposition. In special cases, we can even determine the relative phase between the modes.

All theory, simulations and experiments presented in chapter 2 to 7, have been performed with monochromatic and fully coherent light. In chapter 8, we theoretically study the response of both the multi-pinhole interferometer and the mode sorter for polychromatic and (partially) incoherent light. The results of these calculations form the starting point for studying applications of measuring the orbital angular momentum of light.