Preface

Lenses play an important role in our life. Our eyes make images of the world around us and are sometimes aided by spectacle glasses or contact lenses.

In daily life we use lenses in CD-drives, in webcams and cellphones, in cameras for photography and observation, in film projectors and search lights, in binoculars for looking at birds, or other far-away objects. Scientific applications of lenses (and mirrors) are found in microscopes and astronomical telescopes. And machines for the production of integrated circuits use huge lens (or mirror) systems to project very tiny details. Lenses are everywhere.

The book presented here has the title "A Course in Lens Design." This title should be understood as follows: the design of lenses is a complicated activity, because it comprises the design of an *optical system* that performs a desired function, but also the design of the *mechanical* parts in which the optics are mounted (and sometimes also electronics and software). Moreover, the design must result in a product that can be manufactured by existing *technology*.

Because optical system design is the first in this chain of activities, the success of later stages depends on its performance. This book is limited to lens design in the sense of design of a suitable optical system for a given application.

As "A Course in Lens Design" is aimed at users who have little knowledge of the subject (an elementary optics course would be helpful, but is not strictly required), it is limited in treatment to the essentials, as will be seen from the description of its contents below.

As in many research and development activities (and in society as a whole) in the second half of the twentieth-century, the "art and science" of lens design was revolutionized by the coming of the computer.

In the past it took an accomplished optical designer several minutes to calculate the path of a ray through a spherical surface. With the computer this "ray-surface time interval" was reduced to parts of microseconds. In the beginning there was the hope that the design of lenses could be automated completely with the aid of computers. After some time it became clear that this was an illusion; the design of lenses makes in many of its stages decisions of the designer necessary. Nevertheless, the use of design software on the computer saves the designer a lot of time and effort.

It remains true that one needs a certain level of expertise to profit from the expertise stored in lens design software programs. This course is intended to build up this expertise; it brings the beginner to a point where he/she can design a variety of lenses and will be able to use a software program with success.

Coming from a career as an optical scientist, I taught myself the subject of lens design; with this book I want to share this experience with the reader.

I found that most books on lens design either gave more attention to the results than to the process of lens design, or drowned the design process in a sea of details on physics, mechanics, and production technology. That does not mean that these books are not useful; when you have mastered the process of lens design, they can provide a wider and/or more detailed view of the subject. With this book I offer a complete method of lens design that is neither too simple nor too detailed. For a wider perspective the book refers to the literature. As one of my professors said: we want to spare the wolf, the goat, and the cabbage.

The book is divided in six chapters.

Chapter 1 contains a short introduction to geometrical optics. The image formation by spherical mirrors, refractive surfaces, and lenses is described. The thin lens is introduced as a useful and simple model of a real lens. An algorithm is given for tracing rays through optical systems in the paraxial approximation. Finally, definition and function of stops and pupils are discussed. The concepts and tools prepared in this chapter are used continuously in the rest of the book.

Chapter 2 gives a description of important categories of optical instruments: cameras, magnifiers, microscopes, telescopes, and of the optics of the human eye. This is useful to understand the function of lenses used in optical instruments.

In Chaps. 1 and 2, the paraxial approximation of geometrical optics is used throughout. It is a simple, but very useful method to describe centered optical systems. In this book, we do not treat the design of noncentered systems.

In Chap. 3, the description of optical systems is made more accurate by considering third-order aberrations. The relation between wavefront errors in the exit pupil and aberrations in the image plane is shown. The formulas for the calculation of aberration coefficients are given and discussed. The aberration coefficients depend on the position of the stop; stop shift equations are given that quantify these effects.

Chapter 4 describes the processes of lens design.

In Sect. 4.1, system specification is treated; also a review of existing lens types is given.

In Sect. 4.2, the paraxial lay out of the systems to be designed is described. The number, powers, and positions of components are determined. The primary chromatic aberrations are corrected. The components are described by thin lenses.

In Sect. 4.3, the formulas for the aberrations of a thin lens at the stop are given. The stop shift equations are used to determine the coefficients of system components. A procedure for the correction of the aberrations of the thin lens model is described that, with some variations, is used in the design examples of Chap. 6.

In Sect. 4.4, a procedure is given to convert the thin lens predesign to a "surface model" by giving thickness. After this the third-order aberrations of the surface model can be calculated.

In Sect. 4.5, the optimization of the design is discussed. Topics of this section are: construction of merit functions, aberration balancing and fifth order aberrations, the mathematics of optimization and the analysis of the optimized design.

In Sect. 4.6, the sensitivity of the design to fabrication errors is considered; a method of calculation of the system tolerances is presented.

In Sect. 4.7, we derive some results from diffraction theory that can be used in lens design, viz. point spread function (PSF), modulation transfer function (MTF), Strehl's number, and Airy radius.

In Chap. 5, the strategies of lens design are reviewed. We consider five fields of application: color correction (with a section on optical materials), degrees of freedom, symmetries, stops and pupils, and correction of field aberrations.

Chapter 6 contains the detailed descriptions of the design of a variety of lenses. This begins with the design of thin systems (singlets and doublets), followed by the design of a telescope, asymmetric two-component systems, triplets and triplet variants, symmetric four-component systems, micro-objectives, and a section on the application of aspheric surfaces with a postscript on diffractive optics.

The book is addressed primarily to beginners in lens design; for instance, people with an education in applied physics or engineering, or students of technical optics.

When you want to learn lens design, it is not enough to read this book. You should begin to design lenses yourself. The book contains 21 exercises that are meant for that purpose. By completing these you will find that, step-by-step, you will become able to make your own designs. In the beginning this will take some time, because you have to do calculations with pen and paper (and a calculator). By using the spreadsheet facility on your computer you can speed up these calculations. When you have mastered the first stages of the lens design process, you can use lens design software to optimize the design. With the designs of Chap. 6, the Zemax® software was used for this purpose.

In most of this book the mathematics is limited to algebra. In some sections mathematics of a higher level is used. These sections provide background material and can be skipped if necessary. Part of Sect. 4.5 and all of Sect. 4.7 belong to this category, marked by an asterisk.

Deurne, 2013 Chris Velzel

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