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Editorial

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Introduction

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Although magnifying glasses have existed since the 13th century, it was only early in the 17th century that Dutchman Cornelis Jacobszoon Drebbel, whose inventions include the submarine and the automatic lens grinding machine, developed the optical microscope while working in London. A few years later another Dutchman Antonie Philips van Leeuwenhoek built a frame for the optics that he made himself and used this microscope for observing biological samples. This is how the amazing success story of optical microscopes that have since became ubiquitous in every branch of science started. Two Nobel Prizes (Zernike, Physics, 1953 and Betzig, Hell and Moerner, Chemistry, 2014) were awarded for direct technological developments in the field of microscopy and, throughout the years, optical microscopes have profoundly contributed to the award of at least 19 other Nobel Prizes.

Microscope objective lenses are perhaps the most important parts of microscopes. They were initially designed and built without much understanding until, in the middle of the 19th century, Ernst Abbe was hired by Carl Zeiss who had been frustrated by the extremely low yield of optical lens production in his eponymous company in Jena, Germany. Abbe subsequently developed the mathematical theory of optical design, leading to the quantitative understanding of mixing glasses of different refractive indices and dispersions in aberration correction, and the relationship between the wavelength, numerical aperture and resolution. He is also credited with developing the mathematical formulation behind one of the most powerful design principles that exists in imaging; the aplanatic condition. In addition, it was Abbe who recognised the importance of the chemist, Otto Schott's work at the Friedrich Schiller University, Jena, and encouraged and supported Schott to establish the glass factory that until very recently had been located only a few hundred metres from the Zeiss factory in Jena. Schott has supplied Zeiss with optical glass for well over a century. Optical design has come a long way since the pioneering work of Abbe but the basic design principles of microscope objective lenses use, such as cemented doublets that permit precise control of chromatic as well as spherical aberrations, lens spacing, thick meniscus lenses, location of the aperture stop, etc. have not changed since Abbe's time. The fact that today's lens designs are done on high powered computers that perform searches for system parameters such as curvatures, thicknesses and glasses on a multidimensional optimisation landscape run for long times puts Abbe's amazing achievements into perspective, as of course he had no access to computers and did all his designs on paper.

Interestingly, van Leeuwenhoek never revealed the way in which he manufactured lenses and it was not until the middle of the 20th century that it was finally ascertained what techniques he used in his lens making. Secrecy is something that lensmakers seem to have in common as today's lens manufacturers guard their design methods and technology as one of their most valuable secrets. To illustrate how much effort lens manufacturers make to protect their secrets the following is a personal story from this author: around 1998 while he was working as a postdoc at the Engineering Department at Oxford University, Dr Rimas Juškaitis (now CTO of Aurox Ltd.) designed a series of experiments aiming to measure aberrations of microscope objective lenses sourced from a variety of manufacturers. One lens, which was the flagship objective of the particular manufacturer, fared particularly poorly. It is still unclear as to how the news got out but this author received a call from an optical designer of that company, whom he had known for a while, asking if he could come to Oxford to check the results before publication. He did make the trip to Oxford and acknowledged the validity of the experiments. Manufacturers had remained true to their secretive nature and published inaccurate prescription data in their patents until a change in the US patent law around 2010 made it mandatory to include at least one working example in every patent.

Even much experienced optical physicists and engineers have little understanding how objective lenses work and those few who use optical design programs to design their own microscopes tend to model objective lenses as ideal, paraxial lenses. This author had certainly shared

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the frustration with other optical physicists in trying to delve into the subtle details of microscope objective lens design and construction and trying to obtain prescription details of the objective lenses he used. Throughout the years there have been only a small handful of papers published on designing entire optical microscopes including objective lenses. The most reliable source of off-the-shelf optical design has been the website lens-designs.com operated by Daniel Reiley who keeps a meticulous record of various optical systems, including that of objective lenses, sourced mainly from the patent literature. Even though there are prescriptions for possibly hundreds of optical systems on that website, there are less than 40 microscope objectives listed.

Herbert Gross and Yueqian Zhang, authors of the three papers in this issue, have set out to systematically review the patent literature with a fine-tooth comb and analyse those microscope objective lenses published during the last decades. So that the readers can appreciate the authority whose work they hold, it is worth briefly describing the astounding credentials of the senior author, Herbert Gross. A physicist by training, Herbert Gross was the Head of Optical Design of Carl Zeiss AG at Oberkochen from 1995 to 2012 who oversaw the design of numerous Zeiss microscope objective lenses, microscopes and other optical systems (the knowledge of which was not used in these papers). He is the editor and the principal author of the five volume series *Handbook of Optical Systems* published between 2005 and 2012 and a world-renowned expert of using optical design in combination with physical optics modelling for optical system synthesis. His lifelong commitment to teaching came to fruition when in 2012 he was appointed Professor of Optical System Design at the Friedrich Schiller University where he has built world-wide recognition as one of the foremost centres of optical design in the world. His teaching material, available online, is a constant source of reference material students have used throughout the years. The work of collecting and interpreting data was done by Mr Yueqian Zhang, a PhD student in Prof Gross's group, whose talent so clearly shines through the pages of the three papers.

The present material will no doubt become seminal in the near future. The authors analysed 448 different microscope objective lenses from the patent literature spanning from 1926 to 2018. The first of the three papers provides a review of microscope objective lenses and their analysis. We learn how lenses have evolved from Lister's initial arrangement to Petzval's flat field design achieved by two separated cemented doublets, then about Amici's method to increase the convergence angle (numerical aperture of the lens). These lenses seem childishly simple in comparison with Abbe's design of an immersion objective lens from 1886 utilising a cemented doublet and a triplet for improved chromatic performance, along with two singlets, both using the aplanatic surface condition to minimise spherical aberration, coma and astigmatism, and to achieve large ray bending. The authors then look at the evolution of optical design of objectives since the 1980s when the design of short working distance, high numerical aperture, and large magnification lenses became distinct from the lower magnification and numerical aperture but long free working distance lenses. The appearance of multiphoton microscopy is identified as the driving force behind the development of low magnification, high numerical aperture, and relatively long free working (~2 mm) distance lenses as with these microscopes zooming and changing pixel resolution can be achieved by varying the angular range and step size of their scanners which leads to the benefit of being able to see a larger portion of sample using a single objective lens. The paper identifies the different classes of design, such as Achromat, Fluorite, or Superapochromat, etc. and their aberration correction. It also discusses ways of variable correction for immersion medium, coverslip thickness, and material. A special section is devoted to the application of the objective lenses, including conventional, confocal, fluorescence, multiphoton, or total internal reflection microscopy.

The second article describes the modules of the objective lenses and their design principles. In particular, it identifies the front, middle, and rear lens groups. The authors discuss how the front group, mostly responsible for most ray bending, hence of positive power, is designed with some residual spherical aberration, coma, and astigmatism with little possibility of correcting the curvature of field and chromatic aberrations. The middle group is used to correct for almost all chromatic aberrations and the residual spherical aberration, coma, and astigmatism left in the system by the front group. The rear group, usually of negative power, is used to compensate for the curvature of field and some astigmatism and has a great role in determining the overall system magnification and marginal ray height at the exit aperture. It is this paper where we also learn that most microscope objective lenses of practical interest have their aperture stop in the middle group. This has great implications in scanning microscopy where the location of the conjugate plane is of paramount importance. The paper also discusses material selection aspects of objective lens design and the role of high order (5th order and above) aberrations. I believe that this paper is absolutely essential for anybody wanting to learn the basic principles of objective lens design.

The final paper describes miscellaneous design principles. Very low and very high magnification systems are included here. There is also a thorough discussion of those lenses that are equipped with correction collars and the way these work. The use of diffractive optical elements, mostly used for their strong dispersive properties, are analysed here and their use in microscope objective lenses is discussed. Very remarkably, there is a section presenting one of the typical approaches in optical design: taking a known design and modifying it for a new application. As an example, a 40×, 0.85 NA lens, originally designed for epifluorescence wide field microscopy is modified for multiphoton microscopy by extending the colour correction to the infrared region and increasing the numerical aperture. This is achieved by first replacing glasses in the initial design with new glasses of different partial dispersion properties. Then, as the final step, the numerical aperture of the lens is increased to 0.95 by adding a quasi-aplanatic singlet before the first lens and reoptimising the middle lens group. The very last section of this paper describes the synthesis of a 40×, 1.2 NA water dipping lens starting from the basic Petzval design (two cemented doublets) and progressing through Amici's layout. Subsequently, the numerical aperture is increased by the introduction of an aplanatic singlet into the front group which is further corrected for chromatic aberration and the curvature of field by the insertion of a rear group. Additional optimisation and changing of the immersion medium of the front group from air to water leads to the final design.

It is important to point out that, in my opinion, only very few readers will initially appreciate the full impact of these papers. In my experience most researchers in microscopy are not sufficiently equipped to understand the shear amount of knowledge that Zhang and Gross convey on these, nearly 100, pages. But these three articles are rare gems: the more the reader delves into the details the more understanding will be developed. These papers, neatly bound and placed on my shelf, will be my constant companion for the rest of my working life. I trust many colleagues will follow suit when they will finally have the privilege of studying these pages.

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