Optimisation of Tube Lens Design from Stock Optics for Remote Refocussing Systems

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The technique of remote refocusing introduced by Botcherby et al. [1] allows the focal plane of a high numerical aperture microscope objective to be swept rapidly without causing mechanical perturbation to the sample. In order to achieve diffraction-limited imaging away from the design focal plane of the primary objective, the output from the primary microscope is passed into a secondary microscope. The magnification of the secondary microscope is chosen so that the overall magnification from the sample to the intermediate image formed at the output of the second microscope equals the ratio of the refractive indices of the immersion media used in the sample and intermediate spaces [1]. Because of this requirement, it is often then necessary for one of the two tube lenses to have a specific focal length.

In order to form a cost-effective tube lens with a specified focal length, the Plossl tube lens consisting of two achromatic doublets from stock optics was considered, e.g. [2]. Given the large number of available stock achromatic doublets, selecting the optimum pair of stock lenses requires a large number of lens pair combinations to be considered in order to obtain diffraction-limited performance for the required focal length, entrance pupil diameter and field angle. In this work, two computer programmes written in MATLAB (MathWorks) were developed: Catalog Generator and Doublet Selector. Together, these programmes realised automatic Plossl tube-lens design from stock optics via the application programming interface (ZOS-API) of OpticStudio (Zemax) ray tracing software.

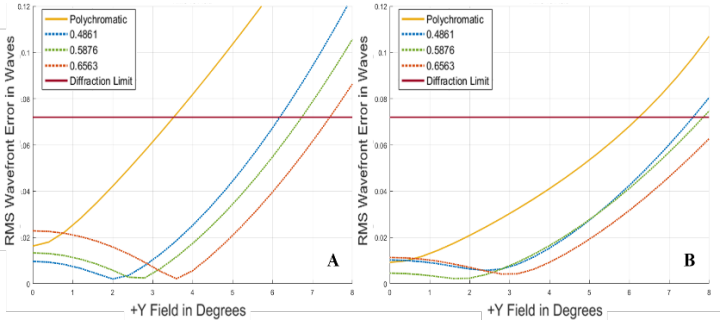

Fig. 1: "RMS v. Field" diagrams of an original tube lens (A) and the optimised tube lens (B). The new cut-off field angle is nearly twice that of the original manually selected system.

To demonstrate the feasibility of our programmes, five Plossl tube lenses were produced for six specific remote-refocusing systems in different light-sheet fluorescence microscopes. Comparison of the results against the original manually selected tube-lens systems showed that the tube-lens systems produced by Doublet Selector generally have a better performance, which is shown in the larger cut-off field angles, see Figure 1, and smaller RMS spot radii. We believe that the software developed is a useful tool for researchers wishing to access cost-effective solutions to achieving microscope tube lenses from pairs of stock achromatic doublets with specified focal length, entrance pupil diameter and field angle.

[1] Botcherby E J, Juskaitis R, Booth M J, et al. Optics letters, 2007, 32(14).
[2] Sparks H, Dvinskikh L, Firth J M, et al. Journal of Biophotonics, 2020: e201960239.