Long-focus low-cost lens designed for biomedical hyperspectral camera

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Abstract. In this work a design of 250 mm F/20 lens for hyperspectral imaging of biomedical micro objects is presented. The designed lens consists of only standard optical elements and does not contain any newly developed component. Its low aperture and small field of view causes that image quality is limited only by diffraction and two optical aberrations – field curvature and chromatic focal shift. That is why an achromatic doublet is utilized as a basic lens component. Its residual field curvature is corrected by a Smith lens – a single plane-concave lens located near the image plane. The components are selected from commercially available ones. A distance between components was the only optimized parameter. Such layout makes the lens cheap and easy to manufacture.

1. Introduction
In recent decades, hyperspectral imaging has been widely used in many different applications, in particular, in biomedicine, for example, in microscopy. There are several ways to obtain a hyperspectral image. For example, in microscopy, tunable filters are utilized for this: liquid-crystal \cite{1} or acousto-optic \cite{2, 3}. An alternative method is to use a special gradient filter \cite{4}, which is a thin film attached to the sensor. Thus, an image of an object is formed at the detector, with each part of the object being imaged in a narrow spectral interval passed by the corresponding section of the gradient filter. There are various methods for restoring a hypercube of data; they are discussed in detail, for example, in a presentation \cite{5}.

2. Hyperspectral imager layout
Optical scheme of the designed hyperspectral camera is shown on figure 1. Standard microscope objective L\textsubscript{1} forms an image at infinity. Lens L\textsubscript{2} focuses it to the sensor attached with a gradient filter \cite{4} with 450 nm to 850 nm spectral range. The Axiom Beta camera \cite{6} with 4096×3072 sensor is used in the developed scheme. The sensor size is 22.5 × 16.9 mm, pixel size is 5.5 μm. Microscope objective L\textsubscript{1} is removable to obtain different optical magnifications for different objects.
The magnification of this system is

\[ \beta = \frac{f_{L1}}{f_{L2}} , \]

there \( f_{L1} \) and \( f_{L2} \) are the focal lengths of L1 and L2 lenses.

Output parameters necessary to design the L2 focusing lens are slightly the same for most models of infinity corrected microscope objectives: field of view (FoV) \( 2w \approx 6^\circ \) and the exit pupil diameter \( D \leq 12 \text{ mm} \). The aperture stop is located close to the microscope lens L1 that is why the designed L2 lens has an entrance pupil rendered forward for some distance \( s \).

In order for the image to fully fit into the sensor format, the focal length of L2 should be equal to

\[ f_{L2} = \sqrt{X^2 + Y^2} / 2 \tan(w) = 270 \text{ mm} . \]

So, the main optical parameters of the L2 lens are \( f_{L2} = 270 \text{ mm} \), F/# = 20 and FoV = 6°.

In this work it is shown how to design the L2 lens. Off course one can found a standard lens with fixed \( f = 270 \text{ mm} \) or zoom-lens and utilize it in this system. But such low aperture gives hope to believe that the lens could be easier, chipper and more compact than any standard lens. So, the mail goal of this work is to show the way to calculate such lens.

3. Lens design

There are two main ways to design a lens. The first is to accurately calculate third order aberrations. The second is the composition of the lens from components with known aberration properties [7].

A low aperture leads to the fact that the aperture aberrations (spherical aberration and coma) do not distort the formed image. Lateral color and distortion are negligible because of small FoV. That is why we can be sure that the optical resolution is restricted by diffraction and chief ray aberrations (field curvature, astigmatism and chromatic focal shift) only.

To make the designed lens not expensive it should be composed of the commercially available components. One of the possible ways to do this and to compensate the residual aberrations is to design the lens consisting of two components. The first one – basic component – is an achromatic cemented doublet. Actually, it is not a problem to found achromatic doublet with the relatively small astigmatism, but the field curvature is significant in all cases even is such small FoV. That is why the second component is a field curvature corrector. It is a so-called Smith lens – a single concave-plane lens located with its flat surface almost close to the sensor. Such location causes that the focal length of the basic component increases only slightly and all values of the aberrations except the image
curvature remain the same as those of the base component. So, the optical scheme of the designed lens is shown on figure 2.

![Figure 2. Layout of the L2 lens.](image)

As a first component it is utilized Edmund Optics achromatic cemented doublet coated for visible and near infrared range with 250 mm focal length. The radius of the Smith lens spherical surface was obtained by optimization in ZEMAX software and selected form available also in Edmund Optics. The glasses utilized in doublet are widely used N-BK7 and N-SF5 from the Schott catalogue, the Smith lens is made of N-BK7.

The distance \( s \) should not be too small for the convenience of mounting the lens. On the other hand, this distance should not be large for the light diameter of the components to be acceptable. In our case the diameters of components are 25 mm that allows us to set \( s = 12 \text{ mm} \).

Finally, optimization was performed, as a result of which the distance \( d \) between the components was determined. Table 1 shows us the obtained design parameters. The focal length of the lens obtained is 275 mm, the distance between the first surface and the image sensor (total track) is \( L = 255 \text{ mm} \), so we could consider our lens as a telephoto lens. The entrance pupil position is 15 mm from the first surface. This is the maximum distance where the light diameters of the components do not exceed the physical dimensions of the selected lenses.

Figure 3 shows a tracing model of the L2 lens (a), the obtained spot diagram (b) and the polychromatic average modular optical transfer function (MTF, figure 3 (c)). The results are presented for the different image points: the central point \( P1 \) located on the optical axis, the intermediate point \( P2 \) and the marginal point \( P3 \).

In figure 3 we could see that the image quality is close to the diffraction limit. The image resolution is about 25-30 cycles per mm within the whole FoV. The theoretical (diffraction) limit is also 30 cycles per mm. The largest aberration is chromatic lateral shift. But it is also negligible – it is less than the Airy disc diameter as we can see in figure 3(b).

### Table 1. Design parameters of L2 lens.

| Surface     | Radius, mm | Thickness, mm | Glass  | Diameter |
|-------------|------------|---------------|--------|----------|
| Entrance pupil | Infinity  | -             | -      | 12.0     |
| 1           | 160.73     | 5.0           | N-BK7  | 13.2     |
| 2           | -105.64    | 2.5           | N-SF5  | 13.4     |
| 3           | -295.75    | 237.0         | -      | 13.5     |
| 4           | -51.68     | 3.5           | N-BK7  | 24.2     |
| 5           | Infinity   | 8.9           | -      | 24.5     |
| Image       | Infinity   | -             | -      | -        |
Figure 3. Ray tracing model (a), spot diagrams (b) and modular optical transfer function (c) of the designed L2 lens.

4. Conclusion
In this report it is shown the application of the composition method for lens design. In our case the designed lens consists of the achromatic doublet and the concave-plane singlet as a Smith lens for the image curvature correction. Such an arrangement of the lens made it possible to select the components of their list of standards, commercially available optical elements with known design parameters, which are significantly (about 2 times) cheaper than custom-made elements. In addition, the tolerances of the Smith lens displacements relative to the basic doublet are quite large, which makes the design of the lens mount fairly simple and technological.

References
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