Field curvature correction in video endoscope lenses through the parameters of air meniscus

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Abstract. The research presents a method to synthesize lens data of an air meniscus built into the optical layout and acting as a correction element that fixes the field curvature of the entire optical system. The practical application of the proposed method is relevant when creating miniature lenses for medical video endoscopes when a small number of lenses and a flat image field for a CCD/CMOS sensor are important. Analytical dependencies for the lens data of the air meniscus are obtained and significant conditions for the field curvature correction are formed. A numerical example of a front stop lens design is demonstrated and confirms the correctness of the formulated conditions. A comparison of the aberration values of the original lens and an upgraded system is carried out. It is shown that, the values of the field curvature and astigmatism have been compensated as a result of introducing the synthesized parameters of the air meniscus into the optical layout. The correction is achieved while keeping the values of coma, distortion, focal length, and optical system total length at the level of the initial values.

1. Introduction
Modern video endoscope lenses possess a range of outstanding characteristics that distinguish them from regular telephoto lenses. Due to the miniaturization of the lens itself and dimensions of CCD/CMOS sensors such optical systems have small focal lengths (from 0.7 mm to several millimeters). The endoscope lenses usually have illumination systems and therefore they may have relatively low values of F# numbers (up to 3.0 and below). Thus, along with small entrance pupil diameters it leads the situation when the effects of diffraction are noticeable [1]. The systems provide wide and ultra-wide fields of view in the object space that imposes a number of restrictions on the choice of the optical layout and its aberration correction.

To reduce transverse dimensions of the front part of wide-field video endoscope objective lens it is possible to use an asymmetric optical layout, where the entrance pupil coincides with the first surface of the optical system or is located in the object space [2]. It should be noticed that a similar layout of the optical system is used both for video endoscope lenses, for example [3–4], and for front stop (pinhole) lenses for CCTV systems [5].

The layout asymmetry relative to the plane of the aperture stop along with high values of fields of view leads to difficulties in correcting such aberrations as coma, distortion and lateral color. Nevertheless, when using multi-element detectors such as CCD/CMOS sensors the most careful attention must be paid to eliminate the astigmatism and the image surface curvature. The latter is often
not completely corrected due to the small number of optical elements and the lack of components with negative optical power.

The importance of researches in the area of a complete or partial field curvature correction is confirmed by studies [6–9]. In study [6] to correct field curvature the parameters of a front thick meniscus lens are used including the variant of meniscus with positive optical power. In [7–8], the problem is solved by using GRIN lenses i.e. when the lens refractive index is not constant. If it is impossible to correct the curvature of the image surface using the parameters of the optical system, the image quality can be improved by selecting the curvature of sensor's light-sensitive area surface [9].

One more way to solve the problem is to use the composition method of optical system design [10]. According to this method it is possible to create a correction element that will compensate the residual field curvature and/or some other aberrations of the original system. The correction element can be embodied as a meniscus – an optical part (lens) consisting of two optical surfaces with radii of the same sign, separating three media with different refractive indices. The meniscus can be embodied in a form of either a glass lens or an air lens as an air gap between adjacent optical surfaces. The latter is frequently formed when using glass glues. Designing miniature video endoscopes, the aim is to reduce the number of components, avoiding optical radiation losses and keeping small longitudinal dimensions. Therefore, to solve the problem of the field curvature correction in the layout of a front stop lens the use of an air meniscus is preferable. Thus, section 2 presents the method of air meniscus design and section 3 demonstrates a design example where the air meniscus is embedded into the layout of a front stop lens to correct field curvature.

2. Air meniscus design method to correct the field curvature

The goal of this work is to calculate the parameters of an air meniscus that is integrated into a front stop lens layout to correct the field curvature of the entire optical system.

2.1. The optical power of the air meniscus and Seidel coefficient for field curvature

The formula for Seidel fourth sum associated with the field curvature and calculated under the condition of the "relative classical scaling" (focal length is \( f' = 1 \)) adopted in Russia, is generally expressed as follows [11]

\[
\bar{S}_{fv} = -\sum_{k=1}^{q} \frac{1}{r_k} \left( \frac{1}{n_{k+1}} - \frac{1}{n_k} \right),
\]

(1)

where \( r_k \) is the radius of curvature of the \( k_{th} \) surface, \( n_k \) and \( n_{k+1} \) are the refractive indices of the media before and after the surface with number \( k \), respectively, \( q \) is the number of the last lens surface. Formula (1) can be also written as

\[
\bar{S}_{fv} = \sum_{k=1}^{q} \frac{\Phi_k}{n_k n_{k+1}}.
\]

(2)

In formula (2), the quantity \( \Phi_k \) corresponds to the optical power of the considered surface and is determined by the well-known formula

\[
\Phi_k = \frac{n_{k+1} - n_k}{r_k}.
\]

(3)

In order to evaluate the results of synthesis and analysis of the lens with an integrated air meniscus, ZEMAX software for automated optical system design was used [12]. The representation of formulas (1) and (2) in ZEMAX is carried out according to the formulas given in [13], and corresponds to the conditions of so called in Russia "natural scaling"

\[
S_{fv,200} = -\sum H^2 c \Delta \left( \frac{1}{n} \right) = -H^2 \sum c \Delta \left( \frac{1}{n} \right) = -(nh\beta)^2 \sum \frac{1}{r} \Delta \left( \frac{1}{n} \right),
\]

(4)
where $H = -nh\beta$ is the Lagrange invariant ($n$ is the refractive index, $h$ is the axial ray height, $\beta$ is the chief ray angle), $c = 1/r$ is the surface curvature.

Considering the notations and sign rule adopted in Russia and calculating the invariant for the plane of the entrance pupil, formula (4) has the form

$$S_{\mu\nu} = \left(\frac{D}{2}\right)^2 \cdot \text{tg}^2(-\omega_1) \cdot \sum_{k=1}^{ \Phi_1 \cdot \Phi_2} \frac{1}{\Phi_k n_k n_{k+1}},$$  

where $D$ is the entrance pupil diameter of the lens, $\omega_1$ is the object space field angle.

In order to transform the value of Seidel fourth sum from ZEMAX scaling to "classical scaling" for a system with the focal length $f'$, it is necessary to use the formula given in [14]

$$S_{\mu\nu} = S_{\mu\nu} \cdot \left(\frac{D}{2}\right)^2 \cdot \text{tg}^2(-\omega_1) \cdot f' = S_{\mu\nu} \cdot f'.$$

### 2.2. Air meniscus axial thickness

The key aspect of the synthesis of the air meniscus as a correction element is connected with the influence of the axial thickness of the meniscus on its optical power. It can be seen from formula (5) that obtaining the value of the optical power of the air meniscus with the opposite sign in relation to the sign of the optical power of the original system is fundamental for compensating the entire system field curvature.

Consider an arbitrary meniscus that is shown in figure 1. It has an axial thickness $d_0$ and surface radii $r_1$ and $r_2$, separating three arbitrary media with refractive indices $n_1$, $n_2$, and $n_3$, respectively.

**Figure 1.** Meniscus layout and its lens data.

Generally, Seidel fourth sum of such a meniscus according to (1) and (2) has the form

$$S_{\mu\nu} = \frac{n_2 - n_1}{n_1 r_1} + \frac{n_3 - n_2}{n_2 r_2} = \Phi_1 + \Phi_2,$$

where $\Phi_1$, $\Phi_2$ are the optical powers of the first and second surfaces of the meniscus, respectively.

Its optical power, according to (3), is determined by the expression

$$\Phi_m = \frac{n_2 - n_1}{r_1} + \frac{n_3 - n_2}{r_2} - \frac{d_0 (n_2 - n_1)(n_3 - n_2)}{n_1 n_2 n_3} = \Phi_1 + \Phi_2 - \frac{d_0}{n_2} \Phi_1 \Phi_2.$$

Considering formula (6) expression (7) can be rewritten as

$$\Phi_m = n_2 \cdot \left(S_{\mu\nu,1} \cdot n_1 + S_{\mu\nu,2} \cdot n_3 - d_0 \cdot S_{\mu\nu,1} \cdot S_{\mu\nu,2} \cdot n_1 \cdot n_3\right),$$

where $S_{\mu\nu,1}$ and $S_{\mu\nu,2}$ are the coefficients of Seidel fourth sum for the meniscus first and second surfaces, respectively.
From the analysis of formulas (7)–(9), it can be concluded that the air meniscus \((n_2 = 1, n_1 \neq 1, n_3 \neq 1)\) turns out to be positive in optical power if its axial thickness satisfies the following condition

\[
d_0 > \left| \frac{r_2}{n_3 - 1} - \frac{r_1}{n_1 - 1} \right|.
\]

The air meniscus optical power becomes negative if the meniscus axial thickness is in the range

\[
0 < d_0 < \left| \frac{r_2}{n_3 - 1} - \frac{r_1}{n_1 - 1} \right|.
\]

In order to minimize the total length of the optical system relation (11) is preferable when designing a negative power air meniscus. The specific value of the axial thickness from the range (11) should be selected considering the required thickness at the edge of the air meniscus when there are no chips and stresses in the adjacent glass lenses.

2.3. Air meniscus radii and its boundary media refractive indices

Now consider the connection of the air meniscus radii of curvature and the refractive indices of the media adjacent to it with the sign of the fourth sum, and, consequently, the value of the field curvature.

Front stop lenses are characterized by a positive value of Seidel fourth sum (that is, a negative value of the field curvature). In this regard, when synthesizing the parameters of the air meniscus, it is necessary to obtain solutions with a negative Seidel fourth sum (positive curvature). As follows from formula (7), this is achieved under the condition

\[
r_2 > k \cdot r_1,
\]

\[
k = \frac{n_1}{n_3} \frac{n_2 - n_3}{n_2 - n_1},
\]

where \(k\) is the coefficient of proportionality of the radii of the surfaces.

Condition (12) for an air meniscus means that the absolute value of the fourth sum in the negative region increases when the difference between \(r_2\) and \(kr_1\) is greater:

\[
r_2 >> k \cdot r_1,
\]

\[
k = \frac{n_1}{n_3} \frac{1-n_3}{1-n_1}.
\]

Therefore, if maintaining relations (11) and (13), it is possible to synthesize an air meniscus that is negative in optical power with a positive field curvature.

3. Design example of field curvature correction based on the air meniscus synthesis method

3.1. Description of the original lens and requirements for its correction

According to the patent [5] a pinhole-type objective lens is used as an initial front stop optical system. Its main characteristics are:

- focal length \(f = 4\) mm;
- F# number 2.8;
- maximum object space field of view \(2\omega_{\text{max}} = 90^\circ\);
- wavelengths \(\lambda_0 = 0.617\) μm (primary), \(\lambda_1 = 0.434\) μm, \(\lambda_2 = 0.800\) μm;
- entrance pupil diameter \(D = 1.4\) mm;
- entrance pupil position relative to the first surface of the lens \(s_p = 0\) mm;
- maximum entrance pupil shift to the object plane \(s_{p\text{max}} = -0.5\) mm is allowed.
The layout of the original front stop lens embodiment is shown in figure 2 and its lens data are given in table 1.

**Figure 2. Layout of the original front stop lens.**

**Table 1. Lens data of the original front stop lens.**

| № of the surface | Radius $r$, mm | Thickness $d$, mm | Refractive index, $n_0$ | Glass name* |
|------------------|----------------|------------------|-------------------------|-------------|
| 1                | −3.236         | 2.75             | 1.74202                 | STK19       |
| 2                | −3.896         | 0.10             | 1.00                    |             |
| 3                | 6.294          | 2.75             | 1.74202                 | STK19       |
| 4                | −2.917         | 0.81             | 1.80195                 | TF10        |
| 5                | −9.533         | 1.00             | 1.00                    |             |
| 6                | $\infty$      | 0.75             | 1.51522                 | K8          |
| 7                | $\infty$      |                  |                         |             |

Focal length: $f = 3.98$ mm; entrance pupil diameter: $D = 1.4$ mm; total system length: $L = 10.58$ mm

* – glass names are taken from "GOST" catalog [12]

Vignetting coefficients for the off-axis beam with the field angle $\omega_1 = 45^\circ$ are: $\text{VDX} = 0.00000$; $\text{VDY} = -0.35549$; $\text{VCX} = 0.04993$; $\text{VCY} = 0.35552$ (according to ZEMAX software standard).

Figure 3 shows Seidel coefficients calculated for each lens surface and Seidel sums. As it can be seen from figure 3 the total value of Seidel fourth sum in ZEMAX scaling is $S_{IV\text{max}} = 0.042449$. Transforming it to the "classical scaling" value according to equation (6) we have $S_{IV} = 0.340385$.

**Figure 3. Seidel coefficients and sum values of the original front stop lens.**
The value of Seidel fourth sum of the modified lens with a synthesized air meniscus is to be limited to $S_4 = 0.25$ (under condition of "classical scaling") while maintaining the focal length.

Here are some aberration values for the maximum field of view and the primary wavelength: astigmatic difference $\Delta z''_a = 0.06342$ mm; average field curvature $z''_{avg} = -0.12845$ mm; tangential coma (for maximum pupil coordinate) $\Delta y''_t = -0.02119$ mm; distortion $\Delta y''_d = -32.87147\%$.

The graph of the original lens field curvature is presented in figure 4 and shows that astigmatism is corrected for the field zone and the average field curvature is uncorrected and negative.

![Field Curvature](image)

**Figure 4.** Field curvature of the original front stop lens.

### 3.2. Air meniscus synthesis

First, it is necessary to find a position of the air meniscus as a field curvature correction element to embed into the original lens layout. In order to do this, the second component of the original lens, initially embodied as a cemented glass doublet (see figure 2), should be split, thereby forming an air gap (air meniscus) between the two lenses of the component. The schematic layout of the modified lens is shown in figure 5.

![Layout of the modified front stop lens](image)

**Figure 5.** Layout of the modified front stop lens.

The correction air meniscus with an axial thickness $d_4$ is formed by two optical surfaces with $r_4$ and $r_5$ radii and separating three media with refractive indices $n_4 = n_{STK19}$, $n_5 = 1$, $n_6 = n_{TF10}$, respectively.

To calculate the lens data of the meniscus, it is necessary to express the optical power of the modified lens. For this purpose we used a transformation matrix (Gaussian matrix) containing surface contributions and transfer contributions (from thicknesses and media) as follows [15]
\[ G = \prod_{i=1}^{k} \begin{pmatrix} 1 & 0 \\ -\Phi_{k+1} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{k+1} \\ n_{k+1} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{k+1} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{k} \\ n_{k} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{k+1} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{k-1} \\ n_{k-1} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{k+1} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{1} \\ n_{1} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{k+1} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{0} \\ n_{0} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{k+1} & 1 \end{pmatrix} . \] (14)

For the lens shown in figure 5 formula (14) can be rewritten as

\[ G = \begin{pmatrix} 1 & 0 \\ -\Phi_{6} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{6} \\ n_{6} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{5} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{5} \\ n_{5} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{4} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{4} \\ n_{4} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{3} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{3} \\ n_{3} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{2} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{2} \\ n_{2} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{1} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & d_{1} \\ n_{1} & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\Phi_{0} & 1 \end{pmatrix} . \] (15)

Equation (15) has no contributions from surfaces 7 and 8 (figure 5) because of zero optical powers for flat surfaces.

The product of matrices (15) results in a 2x2 matrix, that contains an expression for the opposite sign optical power of the lens in the first column and the second row matrix element. After transformations, the expression for the optical power \( \Phi \) of the lens can be written based on (3) as a function \( \Phi = \Phi (r_4, r_5, d_4) \) as follows

\[
\Phi(r_4, r_5, d_4) = \left[ \left( 1 - \frac{d_4}{n_5} \Phi_5 \right) \left( 1 - \frac{d_5}{n_6} \Phi_6 \right) - \frac{d_4}{n_5} \Phi_6 \right] \cdot \left[ \left( 1 - \frac{d_4}{n_6} \Phi_3 \right) \left( 1 - \frac{d_5}{n_4} \Phi_4 \right) - \frac{d_5}{n_4} \Phi_4 \right] = \Phi_2 + \Phi_4 \left( 1 - \frac{d_4}{n_2} \Phi_2 \right) + \left( 1 - \frac{d_5}{n_4} \Phi_4 \left( 1 - \frac{d_5}{n_4} \Phi_4 \right) \right) - \Phi_6 \Phi_5 \left( 1 - \frac{d_5}{n_6} \Phi_6 \right) \,
\]

Thus, the effective focal length of the lens is also a function \( f' = f'(r_4, r_5, d_4) \) and is defined as

\[ f'(r_4, r_5, d_4) = 1/\Phi(r_4, r_5, d_4) . \] (17)

In its turn, based on formula (1) Seidel fourth sum \( \bar{S}_{IV} \) of the lens is a function of the air meniscus radii: \( \bar{S}_{IV} = \bar{S}_{IV}(r_4, r_5) \). It also follows from formula (6) that the focal length of the lens is the relation of Seidel fourth sum in the "classical scaling" \( S_{IV} = 0.25 \) to Seidel fourth sum in the "relative classical scaling" \( \bar{S}_{IV}(r_4, r_5) \)

\[ f' = 0.25/\bar{S}_{IV}(r_4, r_5) . \] (18)

Considering the focal lengths of the modified and original lenses to be equal it is necessary to get a solution of the air meniscus when functions (17) and (18) are equal to each other and as well as equal to \( f' = 3.98 \) mm. Figure 6 shows a graphical solution that was obtained by combining the given parameters \( r_4 \) and \( d_4 \) of the air meniscus and a variable parameter \( r_5 \).

The parameters of the synthesized air meniscus are finally obtained: \( r_4 = -5.6 \) mm; \( r_5 = -4.168 \) mm; \( d_4 = 1.201 \) mm. Now the compliance of the parameters with conditions (11) and (13) will be checked

\[ k = \frac{n_5}{n_6} \cdot \frac{1 - n_5}{1 - n_6} = 1.74202 \cdot \frac{1 - 1.80195}{1 - 1.80195} = 1.04482 \cdot \frac{1.80195}{1.80195} = 1.04482 , \]

\[ kr_4 = 1.04482 \cdot (-5.6) = -5.851 \text{ mm} \Rightarrow r_4 > kr_4 \Rightarrow S_{IV, F} < 0 , \]
where $S_{IVa.m}$ and $\Phi_{a.m}$ are the Seidel fourth sum and the optical power of the air meniscus, respectively.

$$\frac{r_3}{|n_5 - 1|} - \frac{r_4}{|n_4 - 1|} = \frac{-4.168}{|1.80195 - 1|} - \frac{-5.6}{|1.74202 - 1|} = 2.350 \text{ mm} \Leftrightarrow 1.201 < 2.350 \Rightarrow \Phi_{a.m} < 0,$$

3.3. Modified lens and evaluation of synthesis results
The layout of the modified front stop lens embodiment is shown in figure 5 and its lens data are given in table 2.

| № of the surface | Radius $r$, mm | Thickness $d$, mm | Refractive index, $n_0$ | Glass name |
|------------------|----------------|-------------------|------------------------|------------|
| 1                | $-3.236$       | $2.75$            | $1.74202$              | STK19      |
| 2                | $-3.896$       | $0.10$            | $1.00$                 |            |
| 3                | $6.294$        | $2.75$            | $1.74202$              | STK19      |
| 4                | $-5.600$       | $1.201$           | $1.00$                 |            |
| 5                | $-4.168$       | $0.81$            | $1.80195$              | TF10       |
| 6                | $-9.533$       | $1.00$            | $1.00$                 |            |
| 7                | $\infty$      | $0.75$            | $1.51522$              | K8         |
| 8                | $\infty$      |                   |                       |            |

Focal length: $f^{' \prime} = 3.98$ mm; entrance pupil diameter: $D = 1.4$ mm; total system length: $L = 10.14$ mm

The numerical values of the modified lens parameters and the parameters of the synthesized air meniscus are controlled according to formulas (6)–(8), (16) and (17):
- modified system optical power $\Phi = 0.25125$ mm$^{-1}$;
- system focal length $f^{' \prime} = 3.98$ mm;
- Seidel fourth sum of the modified system $S_{IV} = 0.244172$ (“classical scaling” case), $S_{IV_{zmx}} = 0.030452$ (“ZEMAX scaling” case).
• air meniscus optical power $\Phi_{a.m.} = -0.02928 \text{ mm}^{-1}$;

• Seidel fourth sum of the air meniscus $S_{IV\text{a.m.}} = -0.030714$ ("ZEMAX scaling" case).

Figure 7 shows Seidel sums and Seidel surface coefficients of the modified lens. The graph of the field curvature of the upgraded optical system is shown in figure 8.

![Figure 7. Seidel coefficients and sum values of the modified front stop lens.](image)

**Table:** Seidel Aberration Coefficients:

| Surf | SPHA S1 | COMA S2 | ASTI S3 | FOUR S4 | DIST S5 | CLA (CL) | CTR (CT) |
|------|---------|---------|---------|---------|---------|----------|----------|
| STO  | -0.000000 | -0.000000 | -0.000000 | -0.000000 | -0.000000 | -0.000000 | -0.000000 |
| 2    | -0.001778 | 0.006166 | -0.037308 | -0.062339 | 0.472377 | -0.002991 | -0.011902 |
| 3    | 0.005312   | -0.005621 | 0.001810  | 0.054270  | -0.066472 | -0.004336 | 0.006473  |
| 4    | 0.000377   | 0.002769 | 0.020330  | 0.033593  | 0.395936  | -0.002118 | -0.015548 |
| 5    | 0.018662   | 0.013101 | 0.009211  | 0.037756  | 0.032822  | -0.004812 | -0.003223 |
| 6    | -0.010456  | -0.013893 | -0.018458 | -0.053002 | -0.094943 | 0.005085  | 0.007553  |
| 7    | 0.002564   | -0.001533 | 0.000916  | 0.023174  | -0.014402 | -0.003115 | 0.001862  |
| 8    | -0.000703  | 0.001761 | -0.004407 | 0.000000  | 0.011030  | 0.000423  | -0.001058 |
| 9    | 0.000429   | -0.003074 | 0.002688  | -0.000000 | -0.006728 | -0.000238 | 0.000645  |
| LMA  | 0.000000   | 0.000000 | 0.000000  | 0.000000  | 0.000000  | 0.000000  | 0.000000  |
| TOT  | 0.014406   | 0.003756 | -0.021046 | 0.030452  | 0.729019  | -0.005740 | -0.016930 |

Figure 8. Field curvature of the modified front stop lens.

To compare with the original lens here are some upgraded aberration values for the maximum field of view and the primary wavelength: astigmatic difference $\Delta z_{a} = 0.03164 \text{ mm}$, average field curvature $z'_{a} = -0.01011 \text{ mm}$, tangential coma $\Delta y'_{t} = -0.02100 \text{ mm}$ (for the edge of the pupil), distortion $\Delta y'_{d} = -31.42448\%$.

Comparison of the data in figures 3 and 7 and the graphs in figures 4 and 8 proves that the task of field curvature correction has been successfully performed. It can also be seen from figure 8 that the astigmatism and average curvature for the field zone have been corrected.

The air meniscus embedded into the front stop lens has a negative optical power and contributes a negative value of Seidel fourth sum (positive field curvature) eliminating the residual field curvature value of the original lens.
4. Conclusion

Thus, the problem of field curvature correction for compact video endoscope lens, pinhole lens, mobile phone camera lens may be successfully solved with the air meniscus synthesis method presented in the report. Embedding the designed air meniscus into the original layout makes it possible to eliminate the residual values of field curvature and astigmatism, while maintaining the values of coma, distortion, as well as the focal length and system total length at the level of their initial values.

Using the air meniscus synthesis method a design example was demonstrated and a front stop lens was modified to improve the image quality of the original optical system. The result was achieved due to a precise adjustment and control of the embedded air meniscus aberration contributions especially for the values of field curvature.

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