Folded zoom lenses – a review of patent literature

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ABSTRACT

Folded zoom lenses offer an interesting opportunity for a review of patent literature: they are of a reasonable complexity that the designs are likely to be instructive, they offer a small range of design constraints because of the standardization of CMOS imager sizes and the mechanical constraints imposed on DSC cameras, and there is enough recent activity in awarded patents that a representative sample of contemporary designs can be collected. This paper presents a review of recent patent literature for folded zoom lenses. Zemax models were built for the designs disclosed in 67 patents. For this large set of models, the distribution of paraxial properties and lens materials is presented. For the most-common design constraints, two particularly-similar disclosed designs are compared in detail. Engineering differences between the two disclosed designs are compared to differences in patent claims directed to the disclosed designs; the patents' claims are shown to omit, at least for these two patents, some design differences that seem important from an engineering point of view.

Keywords: Lens design, zoom lenses

1. INTRODUCTION

Folded zoom lenses are commonly used in compact cameras such as Digital Still Cameras (DSCs). The folded optical paths enable a short overall length, allowing a convenient camera shape for users. Figure 1 shows how short overall length is achieved by inserting a fold mirror or prism near the front of the lens, leaving the rest of the optical path perpendicular to the user's point of view; generally, the lenses are also designed such that the image plane remains in the same location across zoom and focus positions.

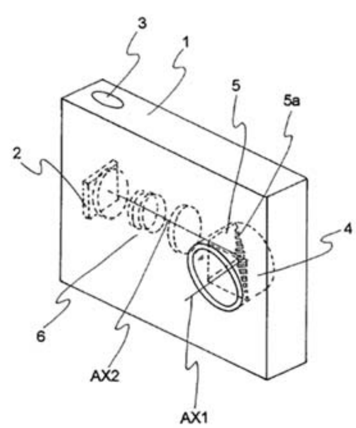

Figure 1: Schematic of a folded zoom lens integrated into a Digital Still Camera, showing a front lens facing the subject (AX1), a folding prism (4), and sensor (2). (Figure is from U.S. Patent 7,692,863).

Folded zoom lenses offer an interesting opportunity for a review of patent literature for several reasons. First, they are of a reasonable complexity that the designs are likely to be instructive. Next, they offer similar design constraints because of the standardization of CMOS imager sizes and the mechanical constraints imposed on DSC cameras. Third, there is enough recent activity in awarded patents that a representative sample of contemporary designs can be collected, thereby

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minimizing the effect of differences in lens fabrication technology. Finally, the recent patent activity has not been so high that it presents too many disclosed designs to model.

Patent literature is an imperfect means for gaining insight into lens design. In general, one or more designs described in a patent, also referred to as disclosed designs, are not necessarily the designs that are actually implemented in products fabricated by the patent's owner. Many legitimate factors can cause an implemented design to be different from a disclosed design; for example, component pricing or manufacturing capabilities can change between disclosure and manufacturing. Another difference between the disclosed design and the implemented design is that important design variables, such as element diameters and real glass types, are often omitted from the disclosed design. Also, tolerances are rarely included in the disclosed design. Finally, errors in the design disclosures can further complicate analysis.

Nevertheless, patent literature is still instructive for gaining insight into lens design. Most importantly, the lens designs disclosed in the patent literature generally provide reasonable image quality. Because of this reasonable performance, other parameters are also of interest. These interesting parameters include the choice of glass types, system size, number of elements, number of aspheres, aberration balancing, paraxial properties, and so on.

Many other papers have compared and contrasted different solutions to the same lens design problem; most notably, each design problem for the International Optical Design Conference has a summary paper describing the different design submissions.[1-4] Other notable reviews include Jonas's review of Double Gauss designs[4], Woltche's reviews of Double Gauss[6] and Anastigmat[7] designs, and Hoogland's review of systematics of photographic lens types[8]. Betensky has published several reviews of zoom lens designs[9-11].

In Section 2, this paper first describes how the set of folded zoom lens patents was chosen. Next, Section 3 shows a survey of the glass types used in the disclosed designs. Section 4 surveys the distribution of paraxial values for these designs, then chooses two designs which are both typical of folded zooms and very similar to each other. Section 5 compares these similar designs on an engineering basis and shows that, despite the many similarities of the two designs, they are meaningfully different. Section 6 compares claims in the newer patent to a design described in the older patent.

2. BUILDING THE MODEL LIBRARY

To generate a large set of patents to consider, the patent database at the U.S. Patent and Trademark Office was searched for patent classification number 359/683 - mechanically compensated zoom lenses. This set of patents was inspected one-by-one to extract patents that included lens prescriptions for folded zooms. To limit the search to contemporary designs, only patents with numbers between 7,000,000 and 8,500,000 were considered.

Zemax models were built of one disclosed embodiment for each of these patents. Generally, only the first-disclosed embodiment was modeled. To be modeled in this study, the disclosure of the embodiment must 1) include radius of curvature, thickness, index, and Abbe number of each surface, 2) have an index and Abbe number that correlate to a real glass, or correspond to an embossed resin, and 3) have reasonably-defined aspheric surfaces. Furthermore, the modeled lens must have reasonable image quality and must closely match the disclosed design in focal length.

This set of requirements is based on what is generally available in the prescriptions disclosed in the patents. These prescriptions omit several values that are important. Most obviously, index and Abbe number are an incomplete description of a glass; many glasses might have the same index and Abbe number, yet have important differences in other properties that might be important to the lens. Reasonable description of an aspheric surface is an arbitrary measure; designs that call for odd aspheres to 20th order were not modeled. Another important variable, lens element diameter, is generally excluded from the disclosures in the patents. This variable is important for achieving the proper vingetting; for this study, the lens element diameters were set by qualitatively examining the disclosed lens layouts, making the models look like the disclosures, and examining the observed ray aberration plots, ensuring that lens flare was well controlled.

To be included in the following comparisons, the models' optical performance had to be reasonable. The modeled focal length had to match the disclosed focal length to within a few percent. Axial spot diameter had to be smaller than 80um. Image size had to correspond to a well-established imager format; this constraint dropped designs that were scaled to f=1. This exercise yielded 67 patents, with 16 assignees. Table 1 lists the patent numbers.

This set of criteria has some important limitations. No attempt was made to compare the tolerances or the effect of element decentration for image stabilization. No attempt was made to evaluate non-sequential properties such as ghost images, dynamic range, etc. Finally, no attempt was made to compare image quality across the different nominal designs.

Table 1: Patent numbers considered in this analysis.

8,437,088	8,427,757	8,369,022	8,351,129	8,325,422	8,279,531	8,279,530
8,270,090	8,254,035	8,243,183	8,218,244	8,184,378	8,154,806	8,149,515
8,111,467	8,089,702	7,986,467	7,982,966	7,940,471	7,911,706	7,855,841
7,835,089	7,830,621	7,817,348	7,800,832	7,791,816	7,782,542	7,773,310
7,692,863	7,684,117	7,630,143	7,626,765	7,623,297	7,602,558	7,589,913
7,567,389	7,529,035	7,515,352	7,511,898	7,499,225	7,486,446	7,471,453
7,466,495	7,463,426	7,443,607	7,443,599	7,417,800	7,411,741	7,411,740
7,382,548	7,379,250	7,375,901	7,339,744	7,315,423	7,301,576	7,274,516
7,227,706	7,227,698	7,227,682	7,218,455	7,215,486	7,193,786	7,173,768
7,085,070	7,079,325	7,068,429				

3. GLASS TYPES

A survey of the glass types used in the disclosed designs can be instructive in many ways. Most importantly, such a survey can inform starting points for similar designs; optimization routines are often challenged by optimization of glass types, so a good stating point is essential. Such a survey can also inform decisions about the reasonableness of the glasses used in an existing design.

Figure 2 shows the Abbe diagram for the glasses used in the disclosed designs. This plot represents 1100 lens elements, from 67 patents, with the first two embodiments considered. The values for cover glasses and ND filters were removed. The figure shows that the full range of available glasses is sampled by the lens prescriptions disclosed in the patents, but that a small number of glasses dominate. The plot also shows that a few values for index and dispersion are greatly over-represented in the patent disclosures.

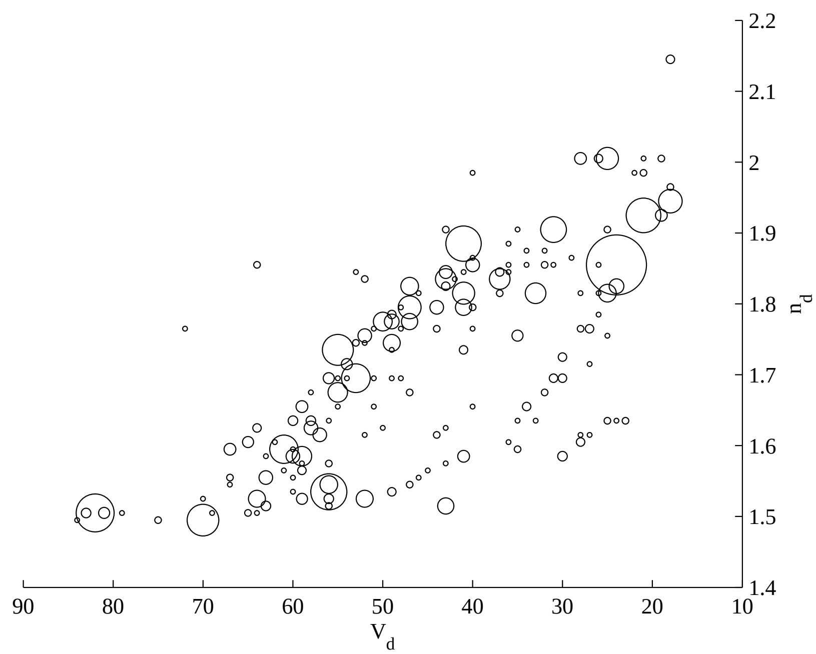


Figure 2: Glass types in the disclosed patents, mapped onto the Abbe glass diagram. The diameter of the points is proportional to the frequency the glasses are used in the disclosed designs.

Table 2: Listing of the most-frequently-used glasses in the disclosed designs, as well as a sampling of the glass types that meet the disclosed index and Abbe number.

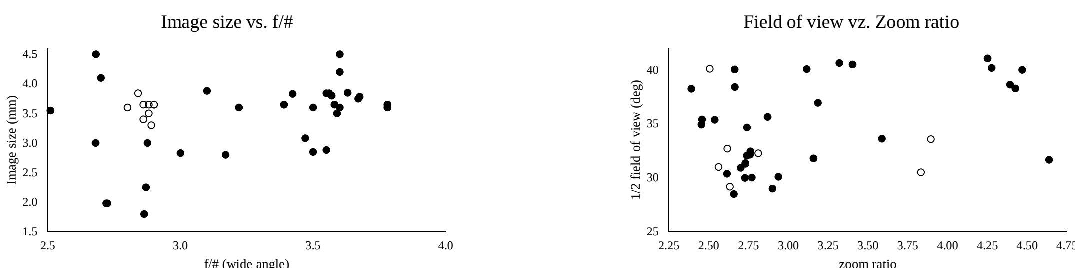
n	V	# of occurrences	glass types
1.855	24	148	FDS90, N-SF57
1.505	82	59	MC-FCD1-M20, FCD1, N-PK52A
1.535	56	54	E48R
1.885	41	52	TAFD30, N-LASF31A
1.925	21	50	E-FDS1, M-FDS1
1.495	70	42	J-FK5, FK5
1.735	55	40	LAK18, H-LaK52

The most-frequently disclosed values for index and Abbe number are listed in Table 2. The most-frequently disclosed glass type is n=1.855, V = 24, which corresponds to glasses such as FDS90 and N-SF57; its prevalence suggests the adoption of high index glasses despite their coloration and workability. The next most-widely disclosed glass type is n= 1.505, V = 82, which corresponds to glasses such as MC-FCD1-M20; its prevalence suggests widespread use of glass molding, which is consistent with the high volumes in this application.

4. PARAXIAL VALUES

The distribution of paraxial design values for the disclosed designs is useful for at least two reasons: 1) this distribution is illustrative of subdivisions in the family of folded zoom lenses, and 2) a detained comparison of designs is most instructive if this comparison is for designs that are paraxially similar.

Image height and f/# are useful parameters for sorting the patent designs because they are closely related to the choice of a sensor; this choice is often a fundamental constraint in the optical design. Image height is closely related to imager format, and f/# is closely related to the number of pixels. Figure 3 a) shows a scatter plot of the image height and f/# of the patent designs. Although the plot shows a wide variety of these constraints, two groupings are evident, both with an image size of about 3.5mm. One grouping has a relatively slow f/# of about f/3.6, the other is relatively fast, about f/2.8. The faster group is highlighted in the figure. Notice that the distribution in image height is much larger than what might be expected from the discrete values for imager size. This distribution may be due to different methods of dealing with distortion and centration, inaccuracies in the disclosed designs, or the use of non-standard imager sizes.



a) b)

Figure 3: Distribution of paraxial properties of the folded zoom lenses. Figure 3 a) shows two groupings of f/# and image size. One of these groupings is shown in open circles. Figure 3 b) shows that the groupings of field of view and zoom ratio are less distinct. The open circles represent the same designs in both plots.

Zoom ratio and field of view are two other common paraxial design constraints. Figure 3 b) shows a scatter plot of these two variables. Two groupings of lenses are evident. One group has a relatively modest zoom ratio of about 2.75 and field of view of about 30 deg, the other group has a higher zoom ratio of 4.5 and field of view of about 40 deg. Note that the designs with the nicely-grouped f/# and image size in Figure 3 a) are not grouped particularly well in zoom ratio and field of view, although he most-common image size and f/# generally fall within the first group.

Five designs fall into the most-common groupings for both image size vs. f/# and zoom ratio vs. field of view. The paraxial and constructional values for these five designs are listed in Table 3. The five patents represent five different assignees. The table shows that, even for designs with such similar image size, f/#, zoom, and field of view, a wide variety of constructional parameters are possible. For example, the design disclosed in the '832 patent stands out for its long length and large number of elements. This difference is likely due to another design constraint; it is the only system in this subset that is nearly telecentric. Table 3 also shows two designs that are quite similar in constructional parameters – the designs disclosed in the '786 and the '800 patents. These most-similar designs will be compared in the following sections.

Table 3: Five folded zoom designs sharing similar paraxial constraints. The two shaded rows, 7,193,786 and 7,417,800, represent the designs to be compared in detail in Sections 5 & 6.

patent #	f/#	1/2 field (deg.)	zoom ratio	likely format	length (mm)	# of groups	# of elements	# of aspheres
7,193,786	2.8	29	2.6	1/2.5"	47	4	9	5
7,218,455	2.9	32	2.8	1/2.7"	57	5	7	6
7,417,800	2.9	31	2.6	1/2.5"	44	4	9	5
7,800,832	2.9	31	2.7	1/2.5"	67	5	10	6
8,218,244	2.8	33	2.6	1/1.7"	32	3	6	8

5. ENGINEERING COMPARISON - 7,193,786 VS 7,417,800

Figure 4 is helpful for comparing the construction of the different embodiments; in addition to the usual lens layout and notation for aspheric surfaces, the lens elements are color-coded to show index and dispersion, following the color code in Figure 2.

Many similarities between the lenses are evident by examining Figure 4. Many of these similarities are common in the other folded zoom designs, despite their grossly different paraxial constraints. First, in each of the designs disclosed in the '786 and the '800 patents, the fold is accomplished via a high-index prism; this design element is also shared by almost all of modeled designs, and is desirable to minimize in optical path of the fold. Next, both of these designs include a high-index singlet with negative power as a front element; this design element is shared by all of the modeled designs that aren't purely telecentric, and is desirable because it helps control field aberrations. Finally, the distance between the first element and the image plane is constant during zooming; this design element is shared by almost all of the modeled designs, and is desirable for simplified packaging of the lens.

Other similarities shown in Figure 4 are less common for the full set of modeled designs. For example, 1) Ray paths are similar, indicating similar powers and positions of the lens groups. 2) Only two groups move, simplifying packaging. 3) The front, stationary group includes a negative aspheric meniscus in front of the fold and a negative doublet behind the fold. 4) Each of the models includes a positive multielement second group behind the stop; this group moves during zoom far more than the other groups. 5) This second group includes a low-index bi-aspheric element. 6) Each of the models includes a weak, simple third group with a small motion during zoom. 7) Each of the models includes a low index bi-aspheric meniscus field flattener. 8) Both of the designs have primarily flint glasses in front and crown glasses in the back.

Despite these many similarities between the two designs, Figure 4 also highlights many differences between the two designs. These differences include: 1) The third group in the '786 design, is a doublet, while the third group in the design disclosed in the '800 design, is a singlet. 2) The front element in the '786 design is meniscus, while the front surface of the '800 design is nearly planar. This difference is significant in a functional sense in that the nearly-planar front surface might offer some attractive packaging options. 3) The bi-aspheric element in the '800 design is nearly at the stop, while the bi-aspheric element in the '786 design is at the far side of the group from the stop. 4) Although the total number of elements is the same, the number of elements in groups two and three aren't the same for the two designs. 5) Group 2 in the '800 design includes a particularly low-index material.

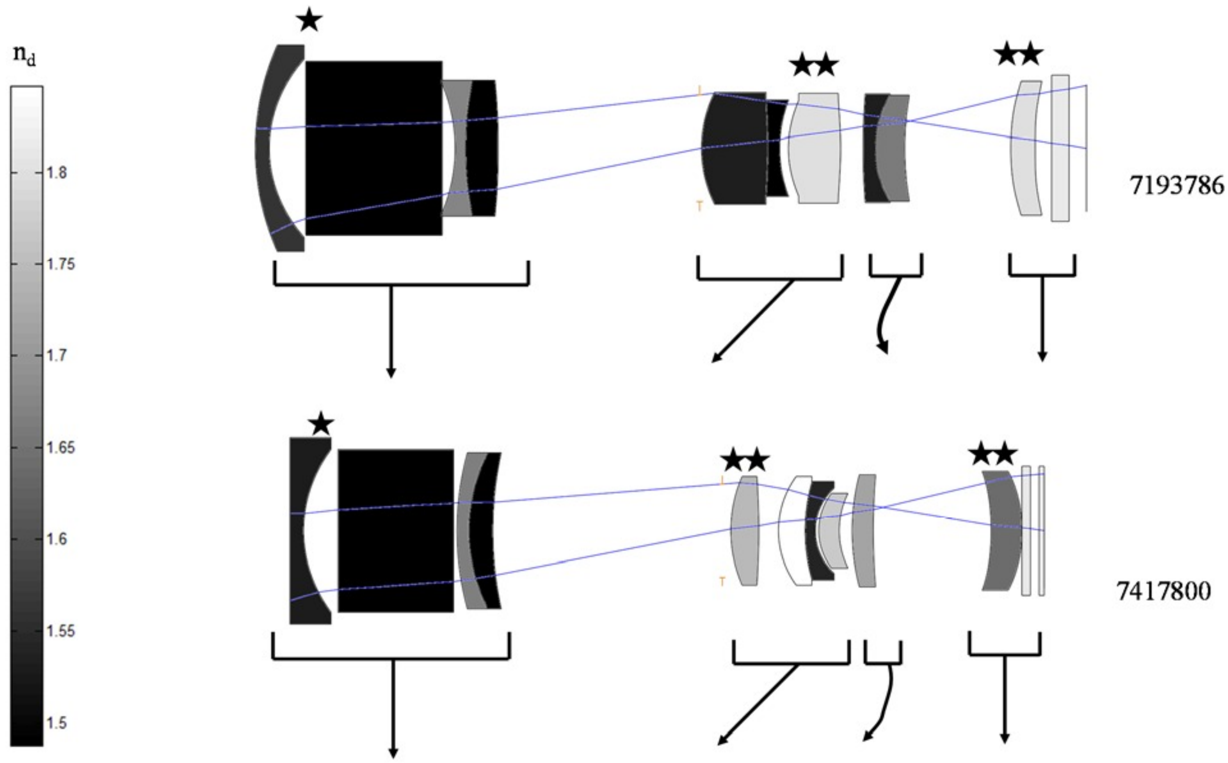


Figure 4: Schematics of the two most-similar designs, showing the chief and marginal rays. Both schematics show the fold prism as a plane-parallel element, both are drawn to the same scale, and both are shown in the wide-angle position. Refractive index is mapped onto grayscale according to the scale on the left. Aspheric surfaces are marked with stars. Zoom groups are represented by brackets, and the motion of the zoom groups is shown with arrows.

Of these design differences, most are unlikely to be bridged by an optimization routine and a merit function that is similar to the defaults in common lens design packages. Taken as a whole, it's hard to think of any optimization routine and merit function that would bridge between the two designs, unless the calculation was specifically designed to do so.

Considering the similarities between the paraxial values for these two designs, it's not surprising that their optical performance is similar. For example, Figure 5 shows that the systems are well corrected for transverse lateral color, although the sign of the Seidel sum is different. Considering the design differences, it's not surprising that the two designs have different ways of reaching this well-corrected performance. Figure 5 also shows that the Seidel aberration coefficient for transverse lateral color is balanced across the lens groups. The '786 design primarily balances color within the lens groups, while the '800 design primarily balances color across the lens groups.

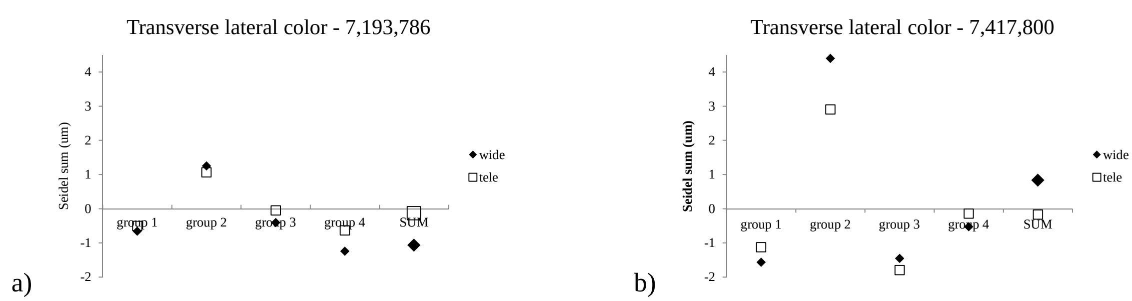


Figure 5: Seidel terms for transverse lateral color for the two most-similar designs, shown on a group-by-group basis. Although the designs are extremely similar, they balance aberrations in very different ways.

6. PATENT COMPARISON - 7,193,786 VS 7,417,800

Patent claims are directed to aspects of one or more designs disclosed in a patent. The claimed aspects of the disclosed designs represent the assignee's intellectual property, and are therefore a legal issue. This section contains a technical comparison, not a legal comparison, of the first claim of the '800 patent with the '786 design disclosed in the '786 patent; this section is not an analysis of novelty and/or inventiveness of the first claim of the '800 patent over the '786 design. See Gortych[12] for more details on how legal issues apply to lens design.

Although the first claim of the '800 patent does not recite the '786 model illustrated in Figure 4 and disclosed in the '768 patent, differences between the first claim of the '800 patent and the '768 design only partially align with the engineering based differences between the '800 and '786 designs described in Section 5.

For example, the first claim of the '800 patent claims 1) a -+++ arrangement in power, 2) a stationary front group, 3) a power on group 2 that is similar to the total power, 4) a moderate power on the front element, and 5) a moderate power on the back of group 1. The '786 design generally meets the aspects (1)-(5) of the first claim of the '800 patent, except that the '786 design has a negative power on the third group. This exception is sufficient to make the first claim of the '800 patent different from the '768 design. (Note that the values for "moderate power" and "similar power" are constrained such that the first claim of the '800 patent does not recite the '768 model disclosed in the '786 patent.) Figure 6 shows graphically how the powers of the various groups compare. Note that these power differences may potentially be bridged by an optimization routine and a merit function that is similar to the defaults in common lens design packages.

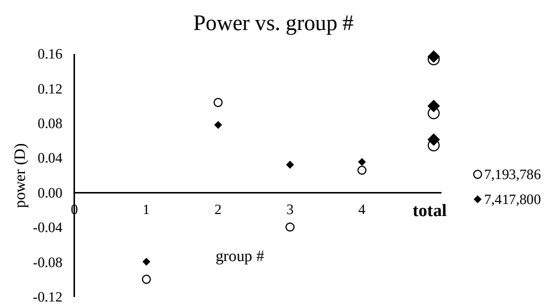


Figure 6: Power distribution for 7,193,786 and 7,417,800.

The other claims of the '800 patent are directed to additional aspects of the design '800 that are not present in the design '786 disclosed in the '786 patent. However, Section 5's engineering differences between the two models only share one element described in the '800 patent - the distribution of elements between the second and third groups.

REFERENCES

[1] Juergens, R. C., "The 2010 IODC lens design problem: the green lens", Proc. SPIE 7652, (2010)
[2] Juergens, R. C, Manhart, P. K., "2006 IODC lens design problem: the lens shuffler", Proc. SPIE 6342, (2006)
[3] Juergens, R. C., "2002 IODC design problem: the diffractive simulator", Proc. SPIE 4832, (2002)
[4] Gardner, L. R, "Lens design problem summary: the solid glass lens", Proc. SPIE 3482, (1998)
[5] Jonas, R. P. and Thorpe, M. D. "Double Gauss Lens Design: A Review of Some Classics Using Modern Methods," in International Optical Design, Technical Digest , Optical Society of America, 2006
[6] Woltche, W. "Optical systems design with reference to the evolution of the double gauss lens," in Proc. SPIE 0237, 201–215, (1980)
[7] Woltche, W. "Major landmarks from the century of anastigmatic lens design," Opt. Eng. 32(8), 1740-1749 (1993)
[8] Hoogland, J. "Systematics Of Photographic Lens Types", Proc. SPIE 0237, (1980)
[9] Betensky, E. I., "Compact zoom lenses," Optics News, Vol. 14 Issue 6, pp.18-20 (1988)
[10] Betensky, E. I., "Zoom lenses for small CCD cameras," in Proc. SPIE. 2539, (1995)
[11] Betensky, E. I. "Forty years of modern zoom lens design" in Proc. SPIE. 5865
[12] Gortych, J., "Lens Design Patents: The view from court space," Optics & Photonics News, June 1996, pp 29-33