

Evolution of zoom lens optical design technology and manufacture

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Abstract. Zoom lens optical designs have advanced for over a century with technology and manufacturing development transforming the capability of zoom lenses. Although there have been many different kinds of zoom lens developed, most fall into three main categories: fundamental, enabling, and improvement technology. Indeed, some technology and manufacturing developments had been crucial to zoom lens optical design development in a pioneering way and yet are now generally considered obvious or even simple. In comparison, other developments are incremental improvements that may be combined together like building blocks. Altogether, the capability of zoom lenses has greatly improved to the extent that today many major performance characteristics are now equal to or come close to matching those of fixed focal length lenses. Some of these characteristics including size, weight, cost, producibility, and general image performance are dependent on widely differing technologies. For example, optical design, coatings, refractive materials, surface types, and the use of computers with suitable optical design software are just some of the technologies that, when combined, have driven the continuous development of zoom lenses and their optical designs. Using zoom lens optical design examples taken from literature and patents, the evolution of zoom lens optical design technology and manufacture is described following a mainly historical order. © 2021 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.60.5.051211](https://doi.org/10.1117/1.OE.60.5.051211)]

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1 Overview

This paper is divided into four main sections that chronologically describe the technologies that individually and when combined significantly influenced the evolution of zoom lens optical design technology and manufacture. The first section concentrates on early fundamental technologies that ushered in zoom lenses, taking them from being ideas or concepts to becoming viable products. The second section focuses on technological improvements that enabled zoom lens optical designs, moving them away from being purely zoom effect lenses and toward being alternatives to fixed focal length (prime) lenses. The third section covers many technologically driven improvements to zoom lenses that brought them to a performance level, making them equivalent to prime lenses for some applications. The last section discusses potential optical design technology and manufacture that may make zoom lenses more attractive in the future, especially in integrated imaging systems.

2 Zoom Origin

When the word “zoom” first applied to zoom lenses is difficult to ascertain. However, it appears that the word came from the field of aviation with the meaning to quickly move closer.¹ Although the word “zoom” was first used in the context of lenses around the 1930s, it became more popular around the 1950s when zoom lenses that kept the image in focus during changes of magnification or focal length, i.e., zooming, emerged.

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3 Early Period—Fundamental Technology

It should be borne in mind that a lack of calculating power meant that early so-called zoom lenses did not produce good image quality but instead mainly provided the imaging effect of zooming that was not available from prime lenses.

Therefore, at the beginning of zoom lens development, the optical design configuration of stationary and movable lens elements and lens groups formed the basic and key technology. Finding good optical design configurations was a huge driver and was an optical design race among optical designers for many years.

3.1 Varifocal Zoom

Around the late 1800s, the so-called zoom lenses started out as varifocal type refractive lenses that typically had a single axially movable lens group with optical power in which the image was not optically kept in focus during changes of magnification or focal length, i.e., zooming. However, by physically changing the lens assembly distance to the image or vice versa, the image could be kept in focus during zooming.^{2,3} Figures 1 and 2 show three examples taken from patents of such lens types from the early 1900s in which there is one axially movable zoom lens group.

These kinds of lenses were commonly referred to as not being true zoom lenses because they did not keep the image in focus throughout the zoom range as would be the case with a parfocal zoom lens. Thereafter, optically compensated zoom lenses appeared; they were also of the varifocal type of zoom lens, which did not keep the image continually in focus during changes of magnification or focal length. These optically compensated zoom lenses had one or more

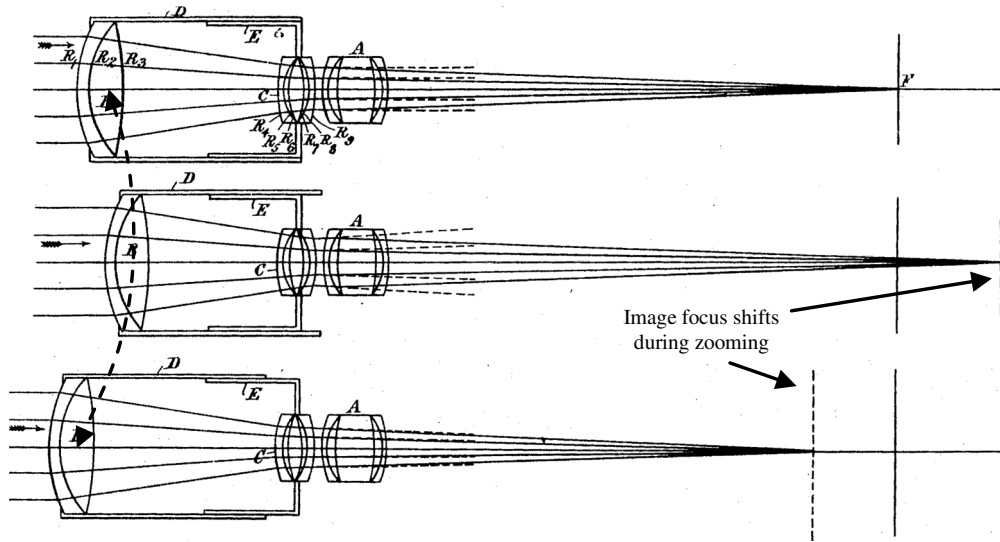


Fig. 1 Dallmeyer, T.R., U.S. Patent No. 756,779, April 5, 1904.

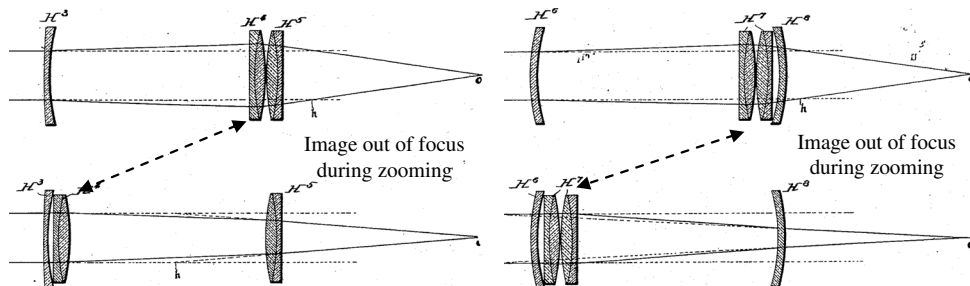


Fig. 2 Allen, C.C., U.S. Patent No. 696,788. April 1, 1902.

movable lens groups, each with optical power. When these lenses contained two or more lens groups, they were moved together in tandem, thereby always having only one physical movement of the optics to keep the image in focus at several positions within the zoom range, usually producing a small but noticeable image defocus at intervening image positions of the zoom range.⁴ Zoom lens optical designs of this type were developed for many applications including still photographic and motion picture camera systems. These zoom lenses took on many forms as camera lenses, projection lenses, auxiliary attachments (usually afocal), and afocal telescopes and were designed for visible and other wavebands such as infrared (IR) wavebands.⁵⁻⁷ Figures 3-5 show early camera and afocal auxiliary attachments for the visible waveband and a much later afocal telescope for use with thermal imager scanning systems operating in the 8 to 13 μm waveband.

One noticeable trait of all early varifocal zoom lenses was their dependence on gears, linear linkages, and single slot cams for the movable optics, partly because multiple slot cams, as required for later developed mechanically compensated parfocal zoom lenses, were not considered readily manufacturable and were possibly imprecise. This became a major technological limitation, especially on zoom lens optical design.

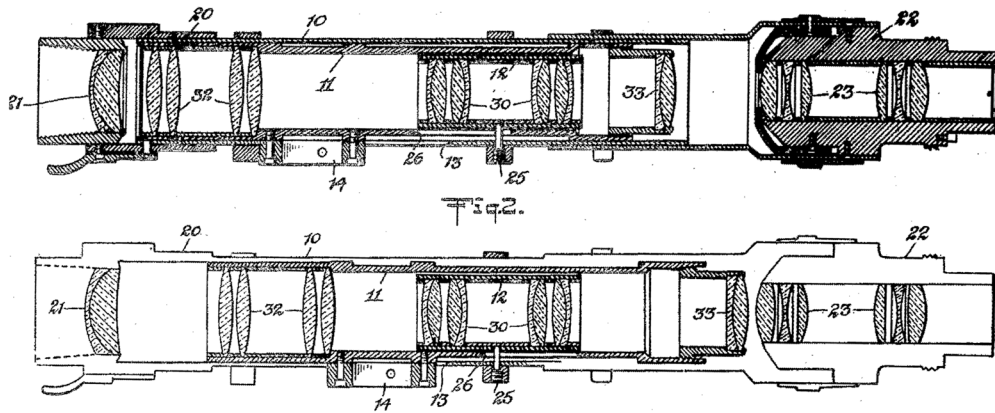


Fig. 3 Back, F.G., U.S. Patent No. 2,454,686. November 23, 1948.

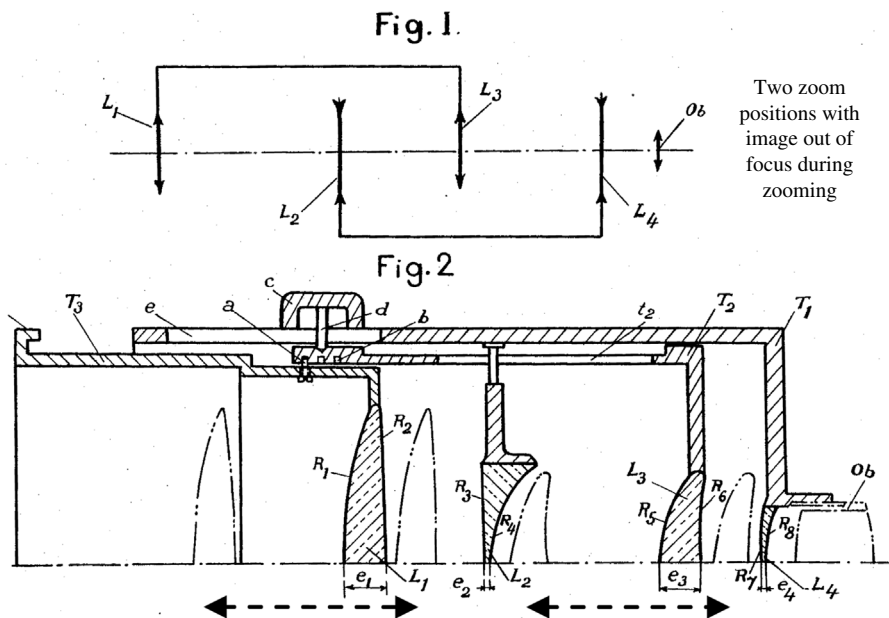


Fig. 4 Cuvillier, R.H.R., U.S. Patent No. 2,566,485. September 4, 1951.

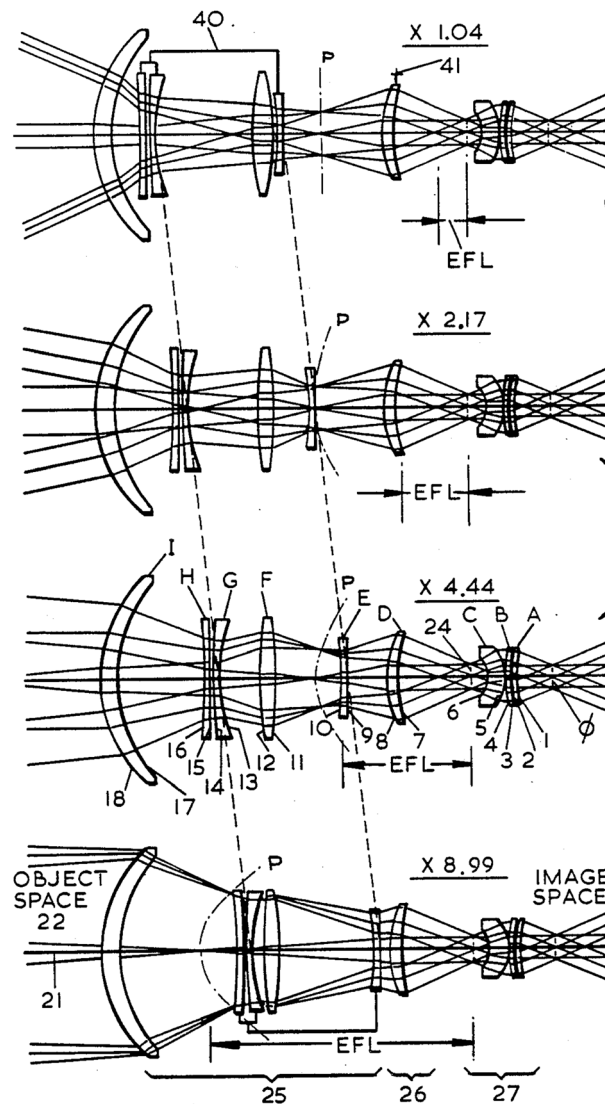


Fig. 5 I. A. Neil, "U.S. Patent No. 4,632,498. December 30, 1986.

3.2 Parfocal Zoom

By about the 1950s, the idea to independently move at least two lens groups each with optical power using sufficiently precise cams meant that it was now mathematically possible to simultaneously change the magnification or focal length of a zoom lens while keeping the image in focus; thus the mechanically compensated parfocal zoom lens was born. Since two powered lens groups can have four power permutations of positive (P) and negative (N) optical powers, i.e., P P, N N, P N, and N P, a frenzy of optical design activity ensued to find the best solution. The victor was the N P zoom power permutation, with the first optical design of this kind invented by Pierre Angenieux.⁸ This optical invention was a watershed event for zoom lenses because it became the basis for many zoom lens optical designs that followed, all of which utilized the much-preferred N P zoom power configuration to generate zoom ratios greater than 4:1 (i.e., 4×) and eventually up to about 100× for broadcast cameras.

3.2.1 N P zoom power configuration

As shown from the patent in Fig. 6, this N P zoom power configuration of the zoom lens groups had a negatively powered first zoom lens group called the "variator" followed by a positively

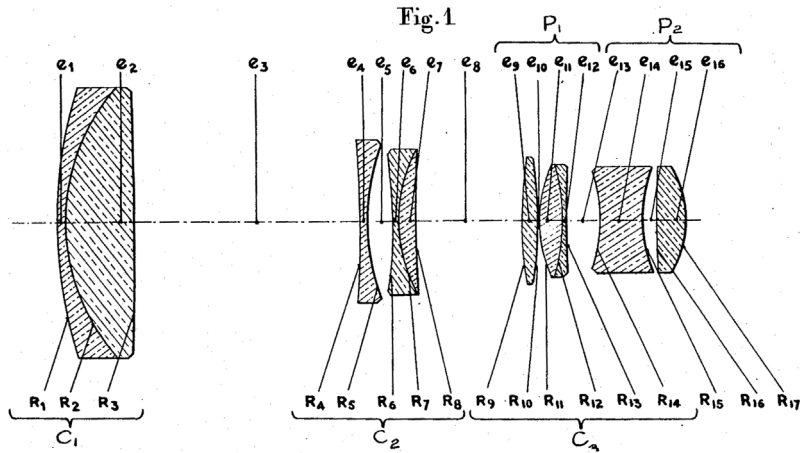


Fig. 6 Angenieux, P., U.S. Patent No. 2,847,907. August 19, 1958.

powered second zoom lens group called the “compensator.” Preceding the variator was a stationary objective lens group that could be used for focusing, and following the compensator was a stationary relay kind of lens group that forms an image. The main duty of the axially movable variator is to change magnification or focal length, hence produce zooming and causing only a small amount of defocus at the image throughout the zoom range. The main duty of the axially movable compensator is to move in a specific relationship to the variator to keep the image in focus and cause only a small change in magnification or focal length throughout the zoom range.

3.2.2 N N zoom power configuration

Slightly before the preferred N P zoom power configuration appeared, the N N zoom power configuration with two negatively powered zoom lens groups was developed.⁹ As portrayed from the patent in Fig. 7, this zoom lens optical design can have symmetrical lens groups with the same optical powers, including the negative powers of the two zoom lens groups. This zoom

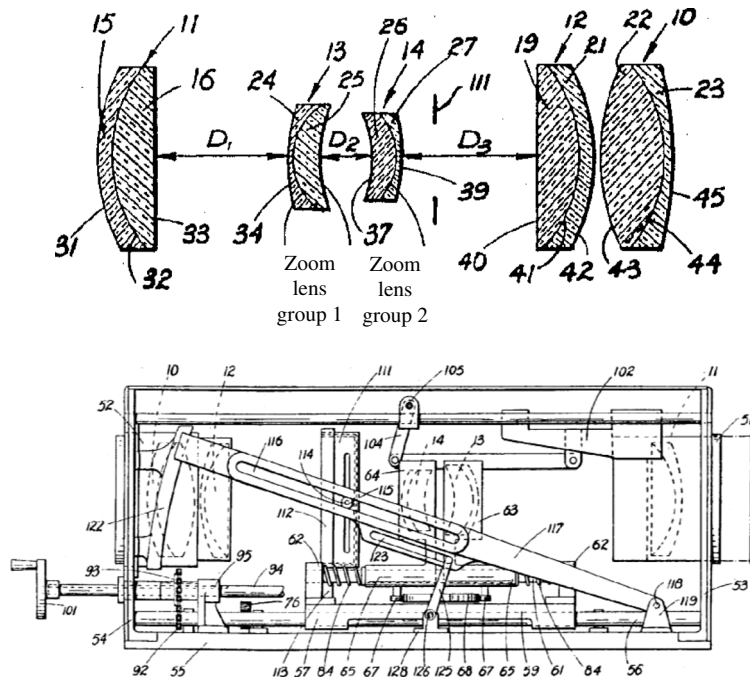


Fig. 7 Hopkins, H.H., U.S. Patent No. 2,663,223. December 22, 1953.

lens optical design can also have a symmetrical locus of movement for the movable negatively powered zoom lens groups. However, by allowing the optical powers and the shapes of the lens elements to change, then higher image performance solutions can be found. The main reason for the original symmetry of the negatively powered zoom lens groups was to simplify the mechanics in such a way that no cam was required, especially not a cam with two different cam slot curves, as illustrated in the lower mechanical drawing of Fig. 7. In this N N zoom power configuration, both zoom lens groups provide variator and compensator functions.

3.2.3 P P zoom power configuration

Another possible zoom power configuration of the two powered zoom lens groups has both zoom lens groups containing positive power; this P P zoom power configuration was found to be good for reducing the aperture diameter of the forward object facing lens elements, but at the expense of only being capable of effectively providing small zoom ratios of about $3\times$ to $5\times$. Due to the likely need to axially move the iris, this P P zoom power configuration was mechanically more complex than zoom lens optical designs with other zoom group power configurations. Partly for the reasons already stated, this zoom lens optical design was less attractive than the others with different zoom power configurations. Therefore, this zoom power configuration has been used less frequently, although some interest in this zoom power configuration has been shown recently partly because of imaging requirements such as telecentricity of digital sensors.^{10,11} Figure 8 shows a basic P P zoom power configuration with single lenses representing powered lens groups and an axially movable and variable aperture diameter iris, which provides a constant aperture at the image over the entire zoom range.

3.2.4 P N zoom power configuration

A last P N zoom power configuration also appeared later, largely driven by the needs of point and shoot still photographic cameras having no reflex mirror.^{12,13} Initially, some very simple optical design constructions appeared, as shown in Fig. 9, in which only small zoom ratios of around $2\times$ were provided. Expanding the optical complexity from having three lens elements and two aspherical surfaces to having many more lens elements perhaps with multiple aspherical surfaces, this type of zoom lens optical design can achieve larger zoom ratios. These kinds of zoom lens optical design have a variable aperture (f -number) at the image throughout the zoom range, which is normally acceptable for point and shoot still photographic cameras. One attractive

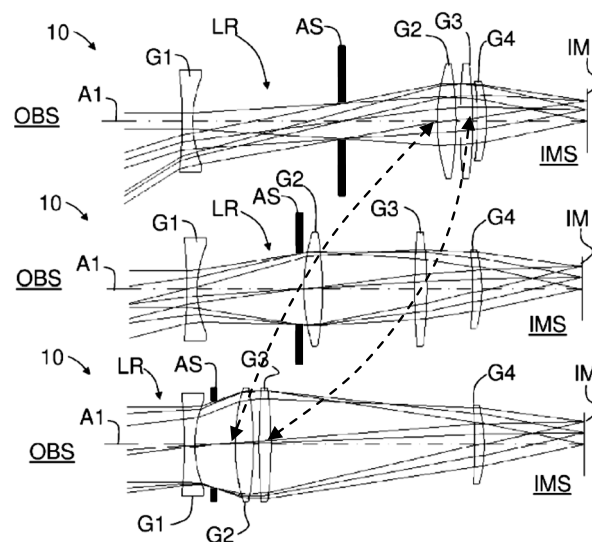


Fig. 8 I. A. Neil, "U.S. Patent No. 9,250,422 B2. February 2, 2016.

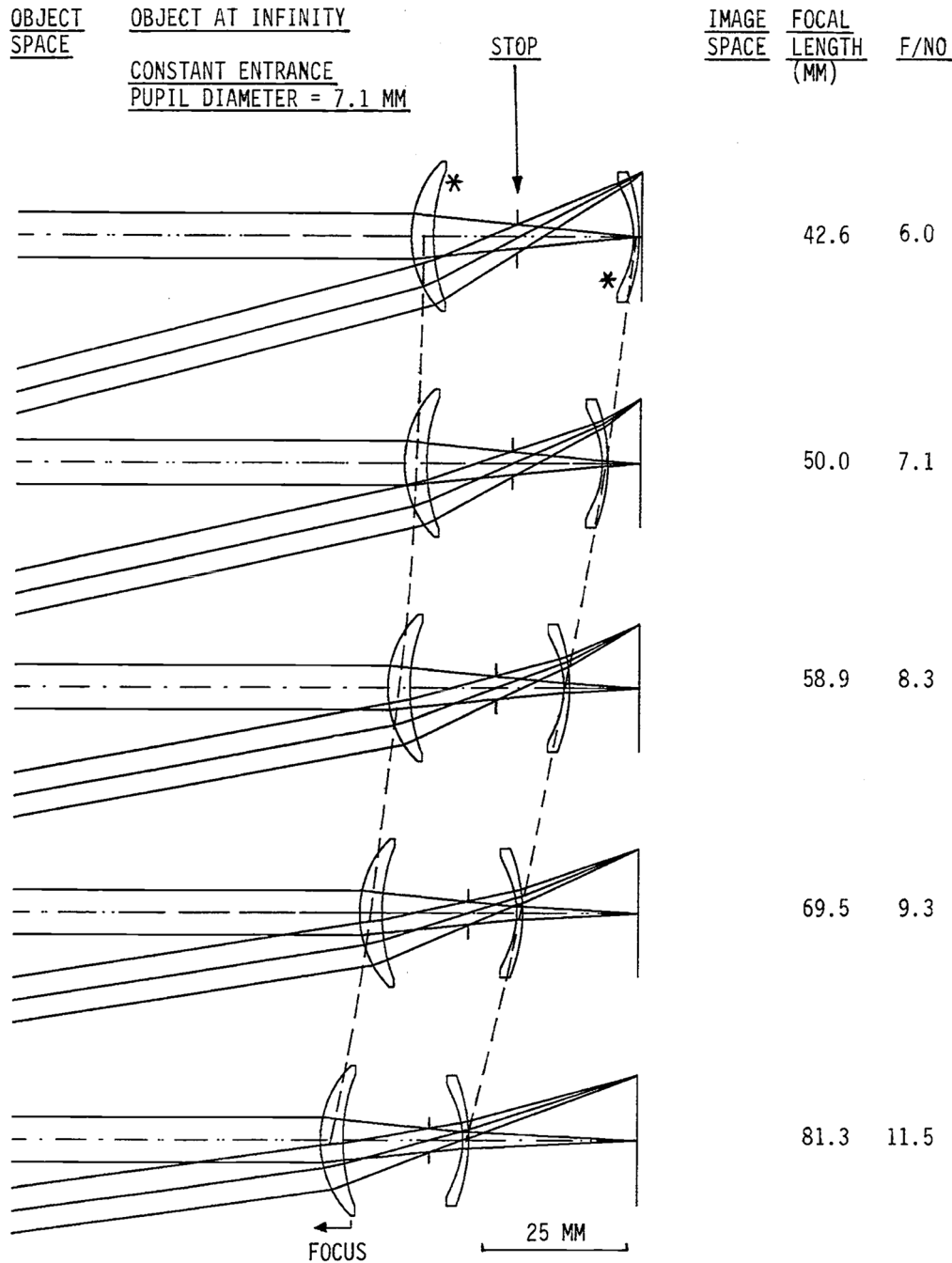


Fig. 9 Compact camera zoom lens.

aspect of this zoom lens group arrangement is that the groups can be readily stored or parked close to the image, so the camera can be kept compact when not in use.

3.2.5 Pseudo-zoom configuration

One other zoom group power configuration having only one movable zoom lens group in which the depth of focus allows the image to be sufficiently in focus for all practical purposes is possible.¹⁴ Depending on the optical power configuration of all of the lens elements and lens groups, this kind of pseudo-zoom lens optical design provides small zoom ratios of around 3× but may be limited to readily available magnifications or focal lengths. The example given in Fig. 10 is an all spherically surfaced afocal zoom telescope for the IR waveband that utilizes high refractive index refractive materials such as Germanium.

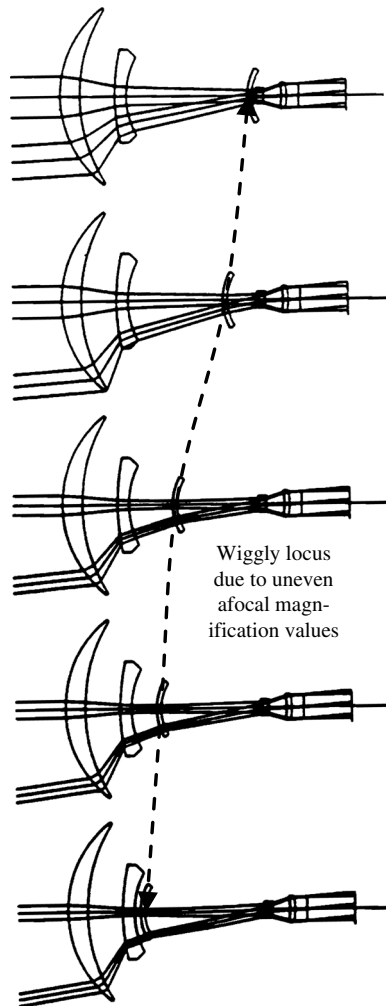


Fig. 10 Pseudo-zoom lens with a single moving lens element.

3.3 Summary of Early Zoom Lens Optical Designs

In summary, all of the afore-described zoom lens systems including the pseudo-zoom lens arrangements were dependent on various zoom lens optical design technologies and associated simple mechanism technology for the movable lens groups. The grand feature of all of these zoom lens optical designs was the zooming effect, with less attention paid to image performance except for later developed zoom lens optical designs, which were dependent on the emergence of later technologies and the advent of digital cameras, which ushered in an era of migration from film-based cameras. Part of the reason for this was two yet-to-emerge enabling technologies that substantially changed zoom lens optical designs.

Therefore, to advance the state-of-the-art of zoom lenses, interrelated technologies were needed to take zoom lenses from being seen as somewhat gimmick lenses to becoming lenses that seriously rival prime lenses in many performance aspects.

4 Middle Period—Enabling Technology

Two enabling technologies that appeared after most basic zoom lens optical designs had been well researched and developed were lens coatings and the combination of computer hardware and optical design software. These technologies may be called disruptive because they transformed zoom lenses from being gimmick lenses to being lenses that were highly competitive with prime lenses. Also, zoom lenses became companion lenses to prime lenses, which in the entertainment market permitted faster and less expensive production of movies and television

series in some instances. This happened because of various factors including fewer lens changes being needed when the camera system could simply be dollied back and forth and the focal length of the zoom lens being able to be adjusted to achieve the desired field of view and perspective. Even with these two enabling technologies, zoom lenses were still not quite on a par with the image performance of prime lenses, but they were certainly starting to close in on them.

4.1 Coatings

The arrival of lens coating technology was truly transformative to zoom lens optical design because one refractive optical surface without a coating would typically experience a 5% loss of light by surface reflection (i.e., 95% transmission) and zoom lenses containing twenty refractive optical surfaces for ten singlet lens elements would lose about 65% of the light input. After including glass absorption, it is likely that the total light loss would be around 70%, so the zoom lens only transmits about 30% of the original light entering the optical system. As bad as that might sound, a total of 10 lens elements is not that many for modern zoom lenses, and a total of 20 or more lens elements is now quite commonplace, meaning that the light loss increases to around 90% and the overall transmission drops to about 10%. For most zoom lenses, large amounts of light loss are not acceptable, and there is also the issue of where the reflected light goes, which may produce severe ghosting and glare due to multiple surface reflections including a narcissus reflection from the sensor and general light scattering. Therefore, without coatings only the very simplest zoom lenses were hitherto available, and one could say that without coatings, practically useful modern zoom lenses would not exist.

4.2 Computer Hardware and Optical Design Software

Affordable computer hardware and optical design software technology was introduced around the 1970s. The optical design effect was dramatic because tools were now available to generate complex zoom lens optical designs containing many lens elements, typically from 10 to 20 lens elements, which are necessary for superior aberration correction to produce low residual aberrations and to provide larger zoom ratios of 10× or more. Also, to properly model the aberrations of zoom lens optical designs throughout their zoom range, it is customary to optimize and analyze many zoom positions at different magnifications or focal lengths, typically from as little as three positions up to 10 positions and in some instances even 20 or more positions. In addition, the same approach is used to properly model the aberrations at different focus positions throughout the focus distance range; thus even a simple zoom lens may need a total minimum of six or seven positions, especially when zoom and focus positions are combined for sufficiently accurate modeling. This means that zoom lens optical design calculations are far more intensive than those for prime lenses. Obviously, more computing power that being available helps in this endeavor, but the optical design software also needs to be suitable to efficiently and fully accomplish the optimization, analysis, and tolerancing process of zoom lens optical designs.

4.3 Optical Design and Artificial Intelligence

It may seem surprising, but optical design software¹⁵ in general, and particularly for zoom lens optimization and tolerancing, has employed algorithms since around the mid 1960s that include damped least squares and statistical probability, which are customary to modern day artificial intelligence (AI) calculations. Managing large quantities of data, as is the case with zoom lens optical design and many AI applications, requires not too dissimilar specialized algorithms, and without this tool it is difficult to imagine how zoom lens optical designs could have been developed anywhere near the point they have now reached.

5 Later Period—Technology Improvement

As zoom lens applications increased and the target specifications became ever more demanding, this led to further improvements in zoom lens optical design and manufacturing technology.

These improvements mainly came from development areas other than optical design, but they significantly influenced zoom lens optical design, sometimes to a great extent. One optical design area that did improve tremendously was focusing, partly because of end-user requirements such as constancy of image performance throughout the focus distance range. Focusing requirements of zoom lenses grew until eventually the optical design of focusing some zoom lenses became as complicated, if not more complicated, than zooming aspects in zoom lens optical design. Several new technologies that influenced and improved the focusing optical design of zoom lenses arose, and glass is the first one of those technologies to be discussed. Of course, some of these technology improvements can be considered alone or combined to magnify their impact.

5.1 Glasses

To attain the high level of image performance now anticipated for zoom lenses and especially where extremely good chromatic aberration is expected, a variety of new glasses arrived around the 1970s that were greatly utilized in zoom lens optical design. These glasses exhibited various optical properties including (i) low refractive index with high V -value (low dispersion) and abnormal partial dispersion, called Fluor crown glasses, (ii) high refractive index with predominantly medium V -value (medium dispersion), called lanthanum-based glasses, and (iii) medium to high refractive index with low V -value (high dispersion) and abnormal partial dispersion, which could be called medium to high refractive index flint glasses. Although some other properties, such as abnormal refractive index change with temperature (dn/dT), large absorption at short wavelength and hence lower transmission, and high cost, were less attractive than ordinary glass types; the overall advantages of using these new glasses surmounted any cost difference. Furthermore, these new glasses were a tremendous benefit for zoom lens optical designs because many aberrations, both monochromatic and chromatic, could now be well corrected in reasonably compact zoom lens optical designs.¹⁶ For example, the long focal length telephoto zoom lens optical design shown in Fig. 11 has a 3 \times zoom ratio providing a 135- to 420-mm focal length range at a full aperture of $f/2.8$ and is well corrected for monochromatic and chromatic aberrations. As shown in the glass graph of Fig. 12 of refractive index versus V -value (inverse dispersion), this zoom lens optical design makes use of the afore-described glasses as well as other traditional glasses, to maximize image performance.

One other glass technology that arose was the development of precision annealed glass discs, which substantially reduced the cost of lens elements, especially ones made from these new glasses that had become popular in zoom lens optical designs because of their ability to maximize performance aspects such as image quality. Indeed, the aberration correction became so good that some zoom lenses¹⁷ by the late 1980s and onward exhibited image performance truly on a par with the best fixed focal length lenses.¹⁸ As shown in Fig. 13, an interesting feature of

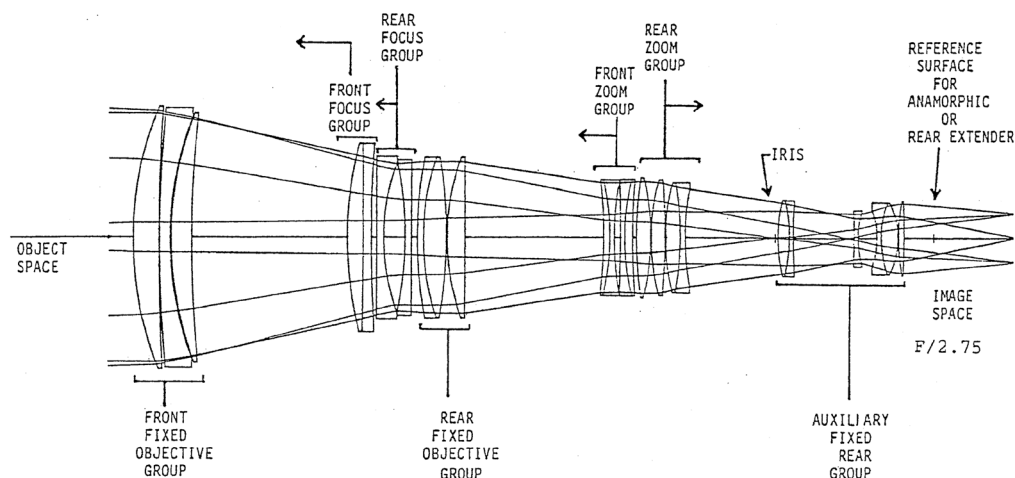


Fig. 11 Long focal length telephoto zoom lens with 3 \times zoom ratio.

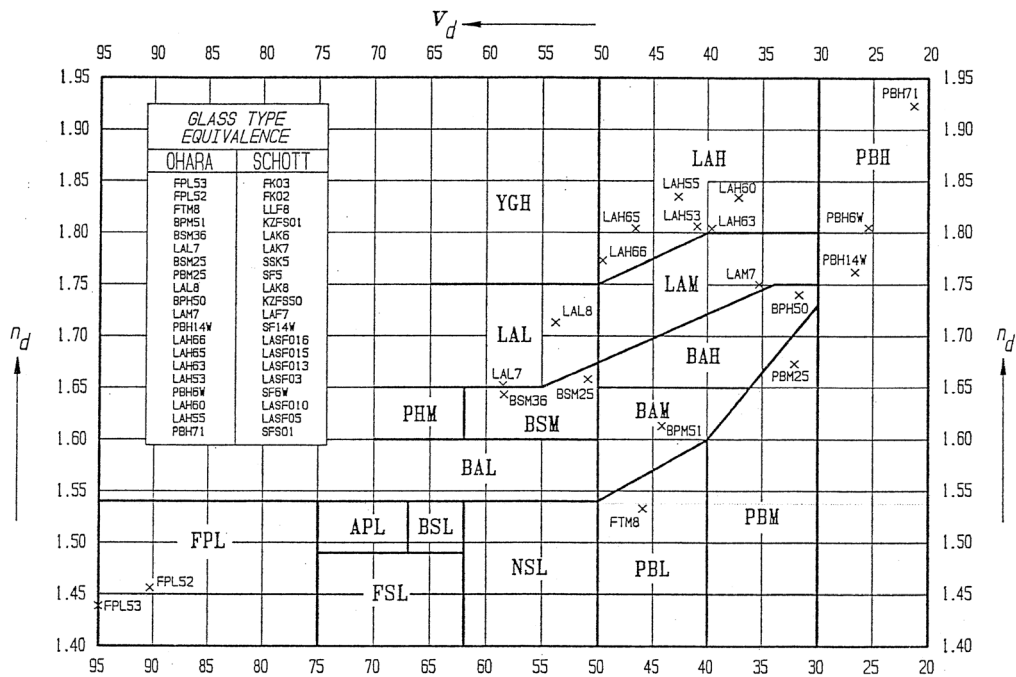


Fig. 12 Glass refractive index versus V-value.

some zoom lens optical designs with a 10X or larger zoom ratio that exhibit very good aberration correction was the use of three powered zoom lens groups Z1, Z2, and Z3.

The second zoom lens group of the original two zoom lens group optical design having an N P zoom power configuration was divided into two powered zoom lens groups Z2 and Z3, having N P zoom powers that formed an overall N N P zoom power configuration. This enabled better correction of aberrations including high order spherical aberration. For this kind of zoom lens, precision and even custom cams having slightly different zoom loci became a prerequisite to achieving the maximum available image performance.

5.2 Focus Breathing

In motion picture imaging, an interesting phenomenon is the change of the field of view when focusing a lens, which is called focus breathing. This pseudoaberration is present with moving images, as in motion pictures or movies, but not with stationary images, as in still photography. Also, it is present with the focusing of most kinds of lenses including spherical and anamorphic, prime and zoom lenses. Apart from producing a sort of distorted look to the images produced, focus breathing can cause a loss of continuity in a scene when focusing back and forth between two objects. For example, say there are two actors in a scene at different distances, with one actor initially being outside of the depth of field but still clearly discernible and the other actor being in focus with the two actors being spaced apart such that one actor is located near the center of the scene and the other actor is located toward the horizontal edge of the scene. Now consider a situation in which the two actors alternately speak their lines to each other; when the first actor is speaking and is in focus, the second actor is not speaking and is out of focus. The problem with focus breathing is that the actor located at the side of the scene goes in and out of focus but is always discernible, but also goes into and out of the scene, meaning that this actor may disappear from the scene when the other actor located near the center of the scene is speaking. This would cause a loss of continuity of the act being captured. In addition, this translates into a ruined shot because one actor is talking to the other actor who may not be visible in the scene, which would naturally appear as a rather odd conversation. To obviate focus breathing, it is necessary for there to be little or no change of the field of view when focusing at different distances. This effect is particularly noticeable when the depth of field is large as is the case for wide to medium angle lenses at or near short to medium focal length zoom positions for zoom lenses. Solving this issue

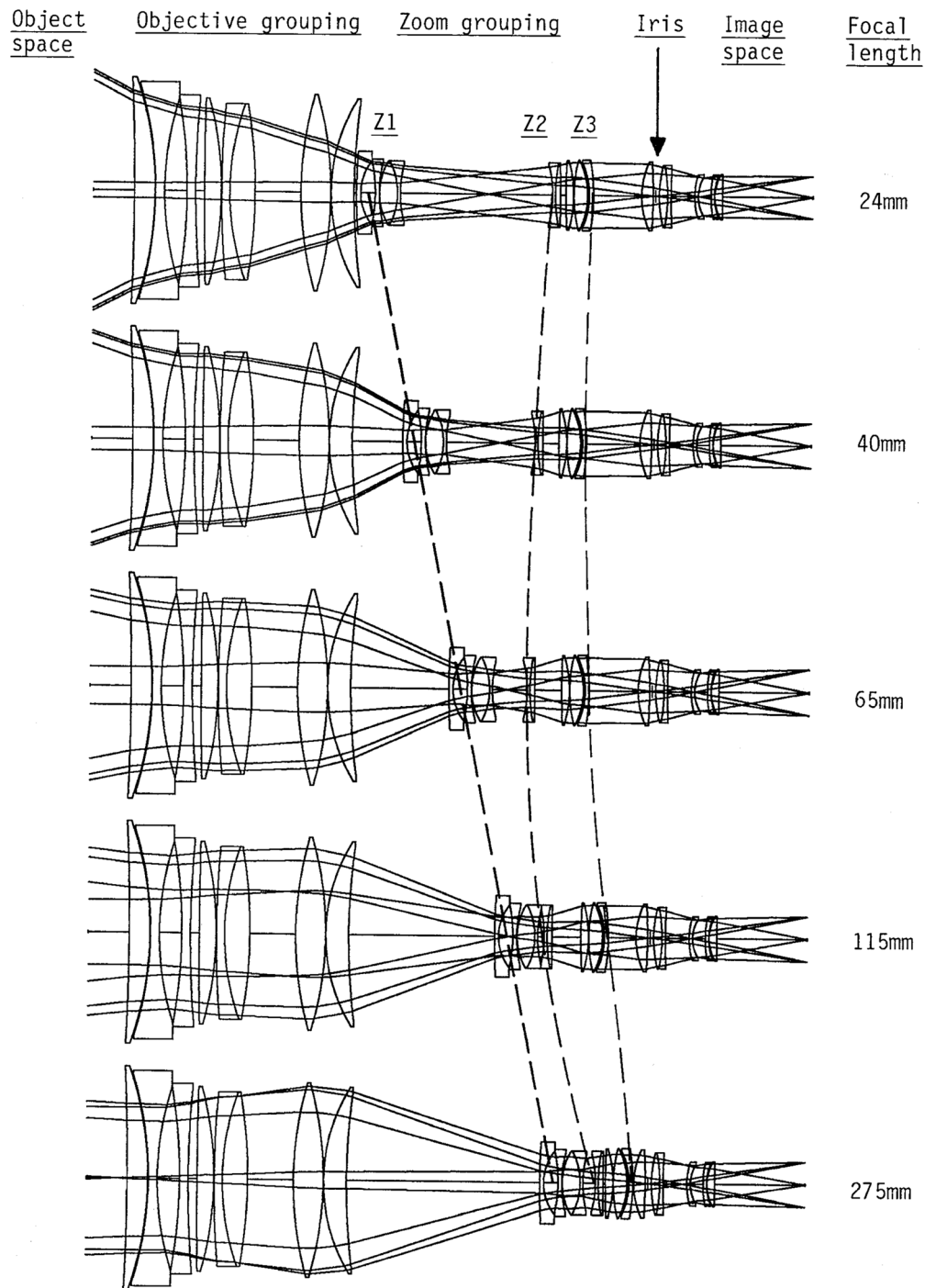


Fig. 13 Short to long focal length zoom lens with 11× zoom ratio.

requires specific focusing lens group arrangements of stationary and movable lens elements usually having different powers. Reduced focus breathing is an important technology for motion picture cinematographic (cine) lenses in general, and in the case of zoom lenses, it had a huge impact on the usefulness of the most advanced optical designs around the 1970s.

An interesting result was that the remarkable optical design advance of the patented Angenieux zoom lens of the 1950s was stymied in cine applications because early zoom lenses of this type produced an excessive amount of focus breathing. To compete with these zoom lenses, the Cooke Varotal 5× and 10× zoom lenses of Rank Taylor Hobson¹⁹ utilized an optical design invention comprising a single movable focus lens group that reduced focus breathing and

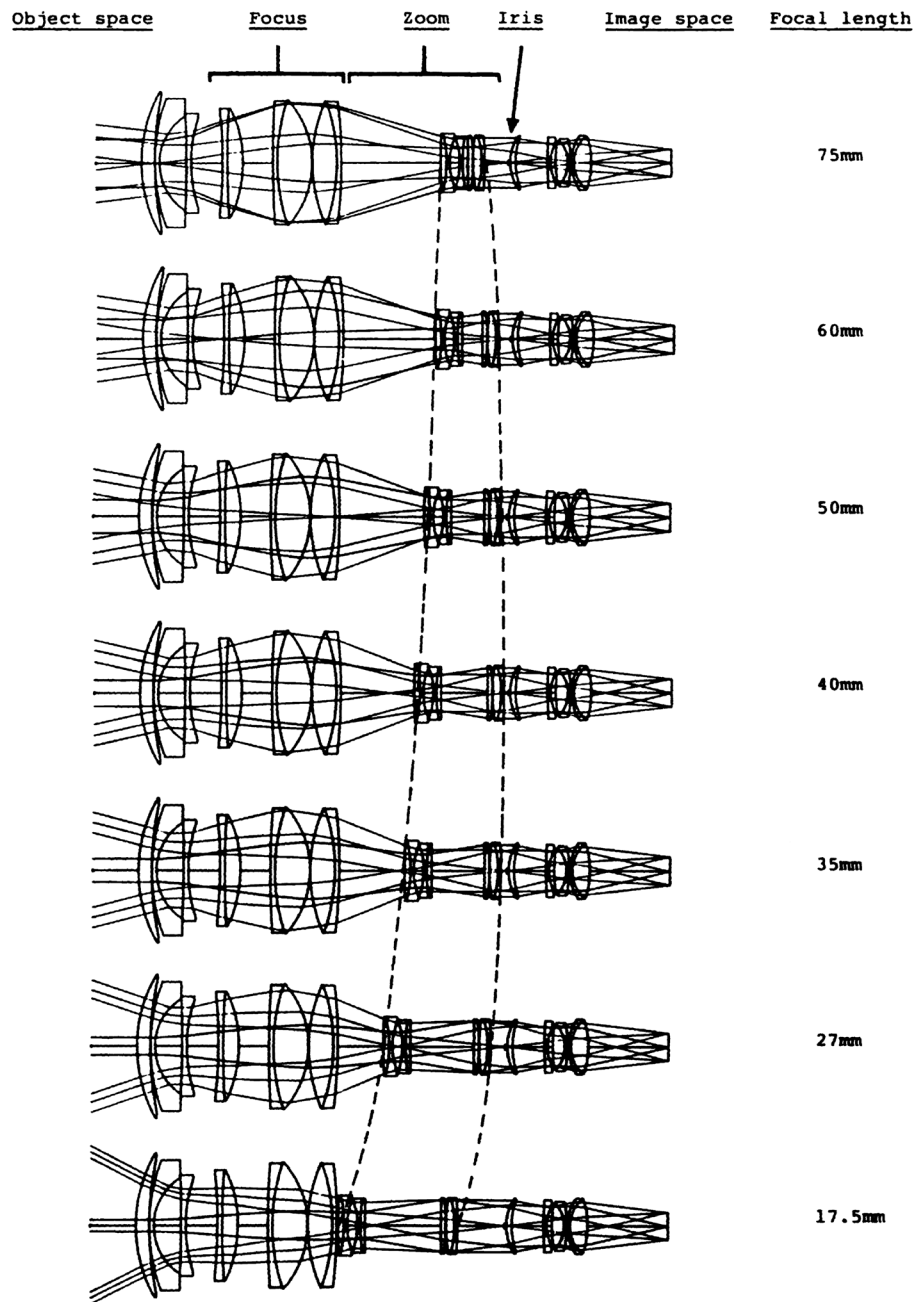


Fig. 14 Wide angle short to medium focal length zoom lens with 4.3x zoom ratio.

an optically compensated zoom lens group arrangement augmented by a focus compensator zoom lens group that was different from the Angenieux zoom lens optical design. This Cooke Varotal optical design was inferior to the Angenieux zoom lens in several zooming respects such as being somewhat less compact, but due to reduced focus breathing, it became a favorite zoom lens of cinematographers. Of course, later zoom lens optical designs housed more sophisticated focusing lens group arrangements, sometimes making use of two movable focus lens groups.²⁰ The zoom lens optical design portrayed in Fig. 14 employs two focus lens groups for focusing and two zoom lens groups for zooming to provide a 4.3x zoom ratio with a focal length range from 17.5 to 75 mm at a constant full aperture of $f/2.8$.

Taking together the afore-described technology improvements and some others such as computer numerical control machining to fabricate precision cams having two or more cam slots, zoom lens image performance reached a level equal to that of prime lenses and in high end

applications such as cinematography, the images shot with zoom lenses now intercut very well with those shot with prime lenses, so that you could not tell them apart.

5.3 Aspherical Surfaces

Thus far, all of the described older zoom lens optical designs depended on spherical or plano refractive optical surfaces. Another advance in zoom lens optical design was the use of aspherical surface technology including pure conic surfaces. This was partly dependent on manufacturing technologies ability to generate nonspherical surface shape profiles and test the nonspherical surface shape profiles. Since the surface accuracy required at longer wavelengths such as 3 to 5 μm and 8 to 13 μm (i.e., 3000 to 5000 nm and 8000 to 13000 nm) is much less critical by about 10 to 20 times than at visible wavelengths in the range of 435 to 656 nm, aspherical surfaces turned up more quickly in IR lenses around the late 1970s and early 1980s.²¹ This also happened partly because there was investment in this technology due to the demand for certain IR lens applications. Also, aspherical surfaces in IR optics could achieve huge cost savings by eliminating lens elements made out of expensive refractive materials such as monocrystalline and polycrystalline germanium. However, with time, aspherical surface manufacturing technology reached a suitable quality level for visible waveband optics, and by around the year 2000, it had been so well developed with many different processes such as grinding, polishing, molding, replication, magnetorheological finishing, etc. that multiple aspherical surfaces could be used in zoom lens optical designs.

There are many potential benefits from employing aspherical refractive optical surfaces in visible waveband zoom lens optical designs, which depend to some extent on their location within the optical design. For example, as shown in Fig. 15, this very wide angle 92-deg field of view zoom lens exhibits a 14.5 to 50 mm focal length range at a constant full aperture of $f/2.2$ and has an aspherical surface located near the front of the zoom lens optical design.^{22,23} In this location, typically within or near the focus lens grouping, the aspherical surface is usually useful in helping distortion correction with a smaller diameter and perhaps fewer lens elements. Locating an aspherical surface near the rear of the zoom lens optical design as shown in Fig. 15 can usually help to correct various axial and field aberrations with perhaps fewer lens elements and may help create a more telecentric light output, which helps to maximize the image quality produced by digital sensors overlaid with micro lenses. Another place to locate aspherical surfaces in a zoom lens optical design is within the zoom lens groups themselves. This enables optimization to smooth out image performance throughout the zoom range and over the field of view at some zoom positions.

In summary, aspherical surfaces basically enhance the overall performance and feature set of zoom lenses whether for size, weight, image performance, close focusing, etc., making them more attractive and competitive with prime lenses. Sometimes a very simple zoom lens optical design as shown in Fig. 9 can satisfy the imaging needs of a specific application, and the use of aspherical surfaces becomes very useful in accomplishing this goal. In general, even though aspherical surfaces may inevitably involve more cost, the increased degrees of freedom of the zoom lens optical design can easily justify the added complexity involved.

5.4 Movable Iris

Having an axially movable iris or diaphragm at the stop in zoom lenses can be advantageous to a zoom lens optical design, particularly in terms of aberration and pupil control. Three of the previously described zoom lens optical designs given in Figs. 8, 9, and 15 already have an axially movable iris that during zooming may open or close either to maintain a constant aperture or to allow a variable aperture at the image. Even though an axially movable iris is in itself a small technology improvement, many small technology improvements can add up in zoom lens optical designs and contribute to raising the overall performance of modern zoom lenses.

5.5 Linear Bearings

A non-optical technology that improved zoom lens optical designs were linear bearings, which began to be used in high-end cine lenses in the late 1980s and in many applications such as the

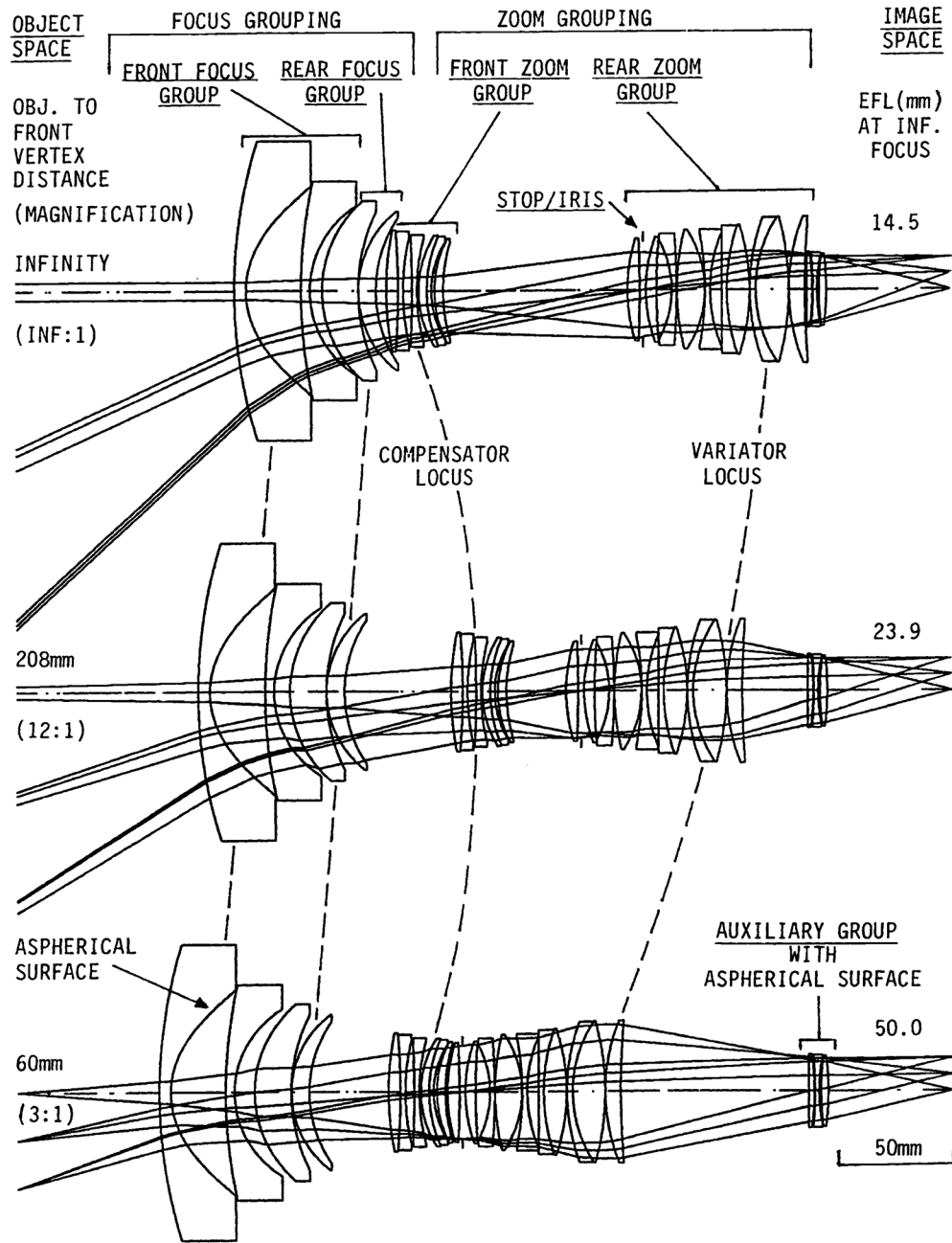


Fig. 15 Very wide angle short to medium focal length zoom lens with 3.5x zoom ratio.

Mars rover zoom lens system.²⁴ Some of the previously described technology improvements including glasses and aspherical surfaces provided higher performance zoom lens optical designs on paper, but to realize this higher performance in as-built zoom lenses, the zoom lens assembly required precisely positioned movable lens groups, especially with small decentration and tilt errors. This can be easier to achieve with linear bearings, which may provide better alignment, lower weight, more reliability, and good boresight alignment. As the focusing optics of zoom lens optical designs became more complicated, as previously illustrated for the zoom lens optical designs in Figs. 11, 14, and 15, it became routine to see two movable zoom lens groups and two movable focus lens groups employed in high-end zoom lens optical designs for many applications including cinematography. All of these zoom lens optical designs benefited in their alignment and stability through focusing and zooming through the use of linear bearings. Aspherical surfaces can be quite sensitive to decentration error, sometimes as small as a few microns

(i.e., ± 0.002 mm) even when located at stationary lens elements. When located within movable lens groups, the decentration error of aspherical surfaces may vary during movement of the lens group, and the use of linear bearings can help to minimize the resulting degradation in image performance over focusing and zooming ranges. The zoom lens optical design portrayed in Fig. 15 is a good example of an academy award winning cine zoom lens from the late 1990s that made use of linear bearings to support two axially movable zoom lens groups and two axially movable focus lens groups.

5.6 Pupil Control

One reason that the 1950s Angenieux zoom lens optical design invention was eventually so successful from an optical design point of view was that the N P zoom lens group powers allowed positioning of the entrance pupil near the front of the zoom lens system at short focal lengths, thus allowing large zoom ratios to be accomplished with moderate lens weight and cost and in particular reduced diameters of frontward lens elements. Many zoom lens manufacturers realized this early on and adopted the N P zoom lens group power configuration for compact electronic news gathering zoom lenses to provide up to around a 50 \times zoom ratio. Also, broadcast television cameras were fitted with other derivative zoom lenses to provide up to a 100 \times zoom ratio. However, breaking the 100 \times zoom ratio barrier with continuous optical zooming required a zoom lens optical design with a completely different methodology to control the entrance pupil. This was needed so that the large diameters of the frontward lens elements were minimized to about 250 mm to keep the lens system practical in terms of size, weight, and cost.

Going from large size to small size zoom lens systems, the same pupil control was required for compact and flexible zoom lens optical designs, sometimes providing very wide fields of view as needed for some applications such as mobile phones. Here, the entrance pupil control is important in minimizing the overall space envelope of the optical package, including reduced diameters of the frontward lens elements and the possible folding of the zoom lens system for better packaging in a restricted space volume.

5.7 Compound Zoom

For very large zoom ratios up to and far exceeding 100 \times , the optical design invention of dividing the zooming function into two separate zoom lens groupings separated by an intermediate image was spawned and thereafter coined a compound zoom lens.²⁵ The basic idea here was to have two zoom ratios from two separate zoom lens groupings, thus permitting excellent control of the entrance pupil location even for lenses with very wide fields of view. For example, a continuous optical zoom ratio of 300 \times could now be attained by having two zoom lens groupings sequentially arranged and having zoom ratios of 20 \times and 15 \times , which when multiplied together gives an overall zoom ratio of 300 \times . One disadvantage of compound zoom lens systems is that the f /number can vary, at least partly throughout the zoom range of focal lengths, at the intermediate image and correspondingly at the final camera image. This can be seen in the 300 \times zoom ratio zoom lens optical design for broadcast television applications²⁶ as shown in Fig. 16. Fortunately, the compound zoom lens optical design characteristic of a slower aperture f -number at longer focal lengths is similar to the conventional 100 \times zoom ratio zoom lens optical design for broadcast television. Therefore, this slower and reduced aperture f -number at long focal lengths as compared with short focal lengths is acceptable given the high sensitivity of modern electronic sensors.

For the afore-described 300 \times large ratio zoom lens optical design, many of the previously described technologies have combined to make this kind of zoom lens optical design possible. In particular, linear bearings was a good technology to utilize to maintain alignment of the two axially movable focusing lens groups and the three axially movable zooming lens groups over large travel distances. Given the total number of 39 lens elements and more than 20 modeling positions used in the optical design software for zooming and focusing as well as optical stabilization, it is evident that many of the afore-described technologies, including coatings, glasses, aspherical surfaces, movable iris, etc., were instrumental in realizing such a complex zoom lens optical design.

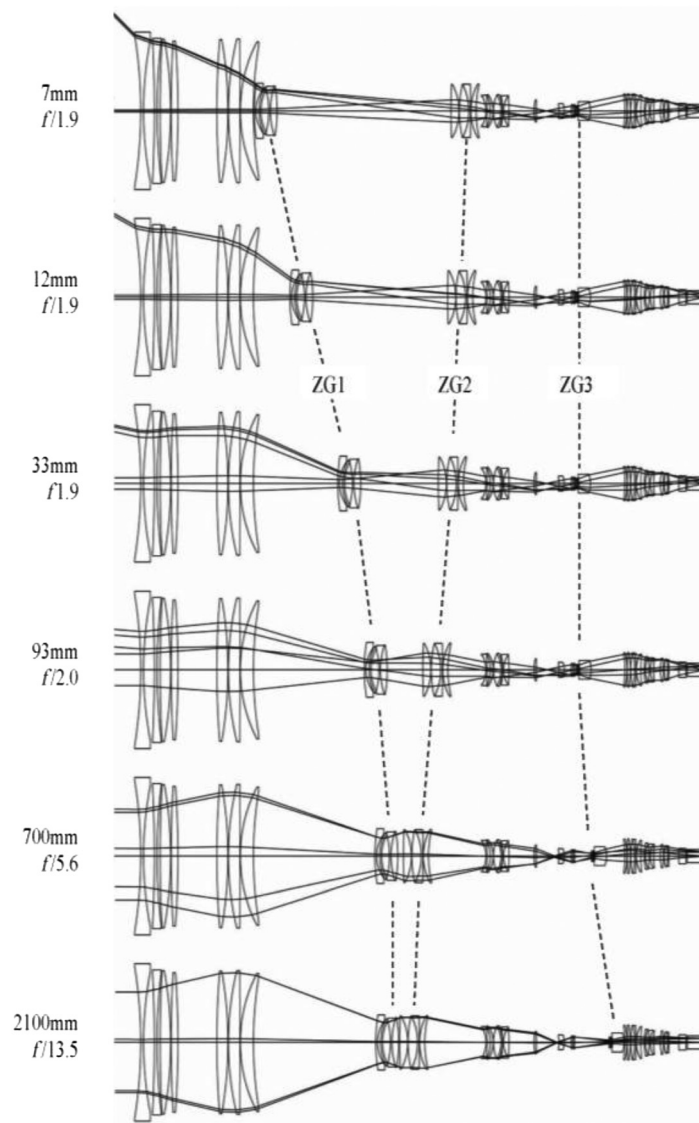


Fig. 16 300 \times zoom ratio compound zoom lens through zoom at full aperture and infinity focus.

For smaller zoom ratios of around 5 \times and wide fields of view, the same compound zoom lens optical design approach can be utilized.^{25,27} The zoom lens optical design rendered in Fig. 17 makes use of the compound zoom lens optical design approach to achieve a 4.8 \times zoom ratio in a compact space volume, with a minimized front clear aperture diameter at the wide angle short focal length zoom position, and to strategically locate three fold prisms. This type of compound zoom lens optical design is well suited for use in small imaging devices with small sensors such as a mobile phone.

The compound zoom lens optical design technology can equally well be used for zoom lenses operating at longer wavelengths such as the 3 to 5 μm and 8 to 13 μm wavebands. The zoom lens optical design shown in Fig. 18 is an example of a compound zoom lens for the 8 to 13 μm IR waveband that provides a 180 \times zoom ratio.²⁸

It is worth noting that, where noncontinuous optical zooming or even no zooming is acceptable, then digital zooming, extenders, or discrete multiple fields of view arrangements can be adopted, which may also obviate the need for compound zoom lens optical designs for large zoom ratios and lessens the need for entrance pupil control. However, these kinds of approaches can have downsides such as image quality degradation and loss of image capture over a period of time.

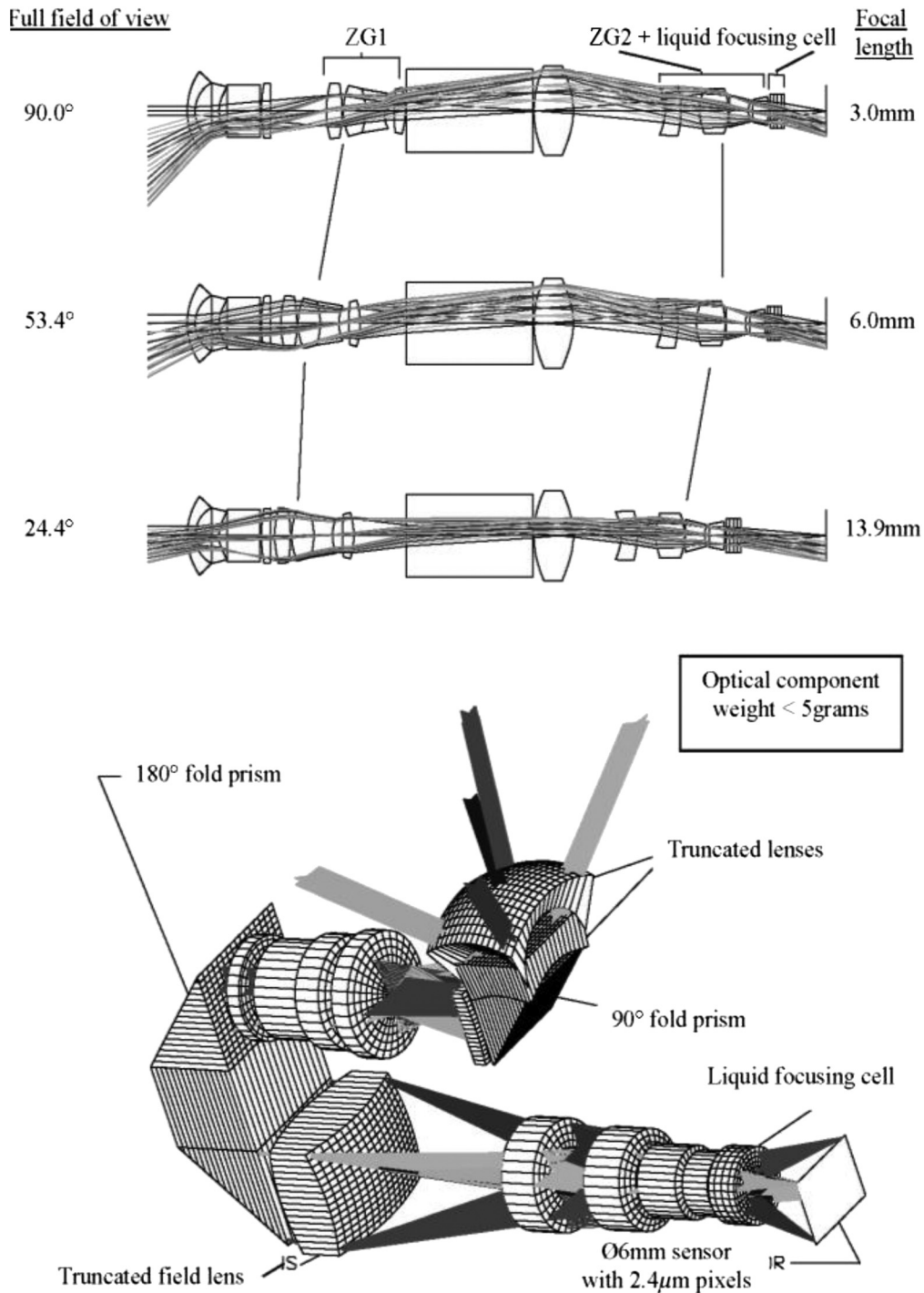


Fig. 17 Compact 4.84× zoom ratio compound zoom lens with liquid focusing cell at full aperture and infinity focus.

5.8 Reflective Zoom

Zoom lens optical designs employing reflective optical surfaces are also possible.²⁹⁻³¹ The example shown in Fig. 19 is an all-reflective zoom system employing an off-axis mirror configuration to achieve an unobscured light path. These kinds of reflective zoom systems tend to produce small zoom ratios up to about 4× and may have wide-angle fields of view of only around 10 deg to 15 deg, but they have the great advantage of operating in any waveband and concurrently working in different wavebands, thus being multispectral and covering more than two

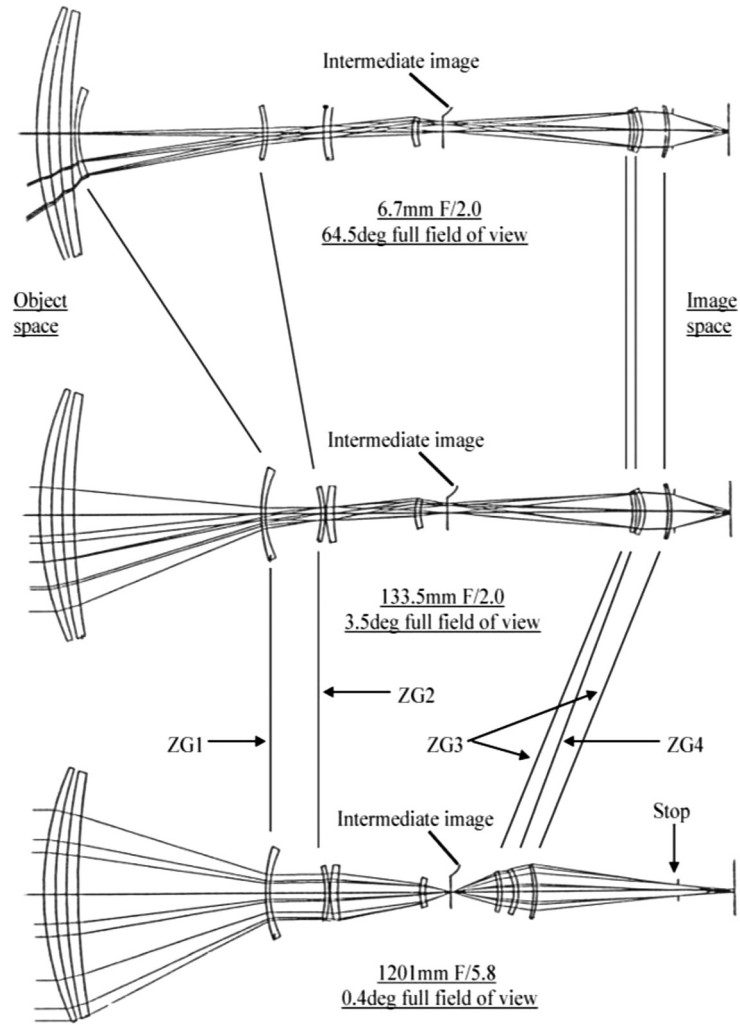


Fig. 18 180× zoom ratio IR compound zoom lens.

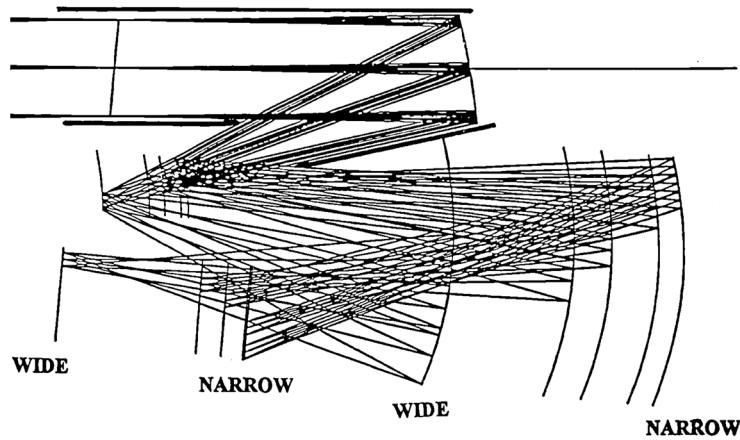


Fig. 19 Reflective 3.5× zoom system.

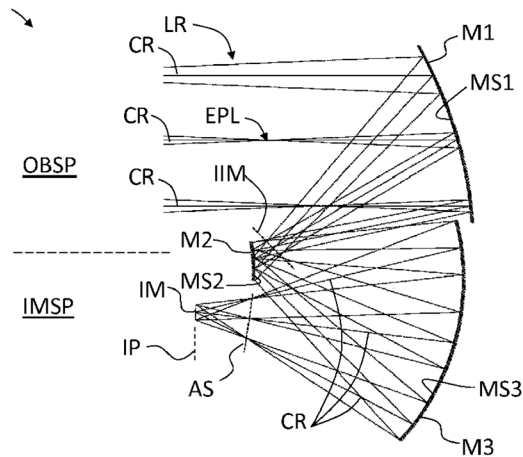


Fig. 20 Three mirror anastigmat system.

wavebands. An added advantage of these reflective zoom lens optical designs is that they can be potentially made athermal and may even be passively athermalized. In comparison, to make refractive zoom lens optical designs perform in multiple wavebands is a difficult task due to a lack of suitable refractive materials that transmit in several wavebands and the need for sufficient control of thermal defocus without loss of aberration correction.

One advantage of reflective zoom systems using off-axis mirrors is that there can be no signature augmentation, which is important in some applications in which the location of the viewer at the image does not want to be detected by the object being imaged. In terms of fabrication of zoom lens optical designs and reflective optical designs in general, there are some interesting manufacturing technologies such as electro-forming³² that are able to produce individual mirrors and simplify the assembly of the mirrors of zoom lens optical designs. This kind of manufacturing technology offers several potential benefits including exceptionally lightweight mirrors, ease of assembly, and alignment of the mirrors because the mirrors can already have their mounts built into the mirror component with the possibility of forming an integrated optomechanical structure that intrinsically may be passively athermalized, as developed for a three mirror anastigmatic (TMA) optical system (Fig. 20).^{33,34}

With the development of freeform type optical surfaces as seen in the design, manufacture, and testing of TMA optical designs and the possible manufacture of reflective components by three-dimensional printing and additive manufacture processes, reflective zoom lens optical designs might become more common.

6 Future Period—Potential Technology

Many new technologies that may transcend the research laboratory are emerging. Some of these potential technologies are derivatives of existing technology and may provide incremental improvement, and a few may be pioneering in new zoom lens optical designs that are possible in the future.

6.1 Anamorphic Zoom

From around the 1960s, anamorphic zoom lenses have been used as cine lenses in the making of wide screen movies. Most early anamorphic zoom lenses had a squeeze ratio of 2× and utilized anamorphic optics containing cylindrical refractive surfaces oriented in one direction attached to the rear of a conventional spherically surfaced zoom lens. Due to large residual aberrations and the creation of a slower aperture optical system, there has been a recent move away from zoom lenses having rear anamorphic optics to those having frontward anamorphic optics, which provide improved image performance at faster aperture. Some of the forward anamorphic optics even employ crossed cylindrical surfaces in two directions usually aligned at 90 deg to one another, thus maximizing aberration correction.³⁵

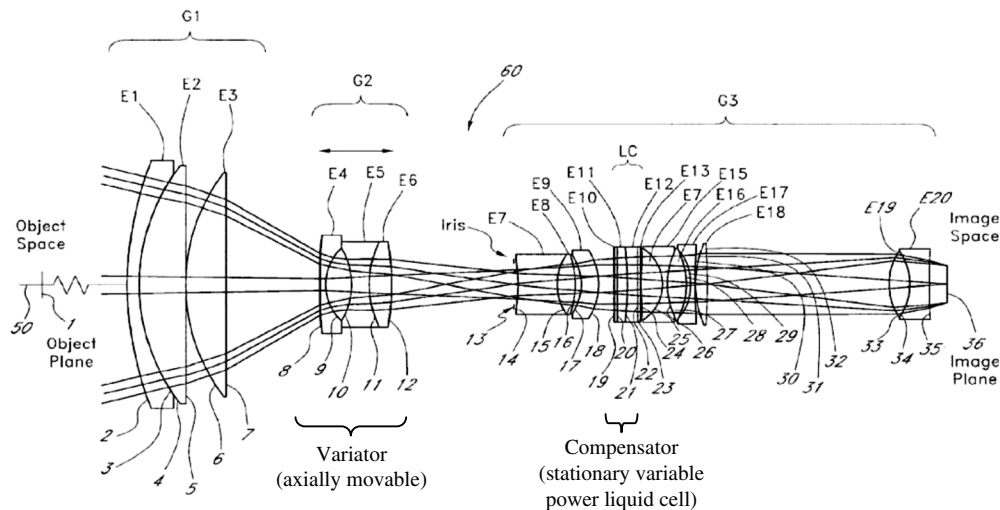


Fig. 21 Hybrid zoom lens system with one movable zoom lens group and one liquid cell.

Another recent anamorphic zoom lens solution is to locate cylindrical surfaces within the zoom lens groups.³⁶ From a paraxial point of view, this may work quite well, but on the basis of high order aberration correction the presence of cylindrical optical surfaces within axially movable powered zoom lens groups could be problematic in minimizing residual aberrations to achieve high performance imaging. Time will tell if this new anamorphic zoom lens arrangement becomes competitive to current anamorphic zoom lens optical design technology and manufacture.

6.2 Liquid Lens

Some of these future technologies include the use of liquids and squishy lens elements materials. Although having existed for some time, these technologies have not been fully accepted in actual products due to various factors such as limited size of clear aperture diameter, concerns about air bubbles forming over time, gravity misshaping of the liquid lens elements, and color change due to ultraviolet exposure over time. Nevertheless, liquid lenses with focusing capability are commercially available from companies such as Edmund Optics Inc., 101 East Gloucester Pike, Barrington, New Jersey.³⁷ These liquid lens devices, which are available with various specifications, can vary focus by changing the shape and power of the liquid lens elements, and many zoom lens optical designs that illustrate the use of axially stationary liquid lens cells with variable shapes and powers to produce a zoom function have been patented. The example shown in Fig. 21 is a hybrid zoom lens optical design³⁸ comprising a variator zoom lens group that axially moves along and a liquid lens cell that acts as a compensator that varies power by changing the liquid lens shape by electrical means. Three advantages of this variator and compensator arrangement are that (i) with only one movable zoom lens group, a cam having one low tolerance cam slot can be used to facilitate the desired movement, (ii) the liquid lens cell does not need an especially large change in optical power to provide a constant focus at the image, and (iii) zoom ratios up to at least 7 \times are possible. By adding another liquid cell adjacent to the image, it is also possible for the zoom lens optical design to control the telecentric light output at the image, making the sensor more efficient and avoiding cross-talk at a sensor pixel level.³⁹ The previously mentioned downsides of using liquid lenses in zoom lens optical designs seem to have stalled the interest in this kind of technology for the manufacture of actual working systems; however, that may change as other technologies mature.

6.3 Curved Sensor

Curved sensors are also a potential technology that can affect the optical design of zoom lenses. The main benefit to zoom lens optical designs are the possible reduction of the total number of lens elements because the overall field curvature or Petzval sum at the image does not have to be

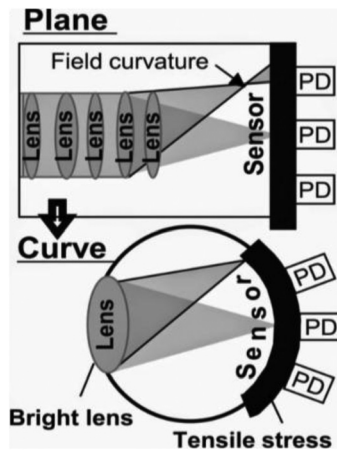


Fig. 22 Curved sensor.

optimized for a flat sensor. The sensor manufacturer may also benefit from a higher production yield, especially for larger sized sensors including sensors from SONY.⁴⁰ The possible reduction in the total number of lens elements is shown in Fig. 22.

6.4 Wafer Chip

Integrated optics and sensors in wafer chips is a fairly new technology that offers the potential to radically change the way all imaging systems are designed and made. This technology could dramatically affect zoom lens optical designs because of its integrated approach to almost all imaging system aspects. Figure 23 shows the component parts of the wafer chip assembly, and Fig. 24 shows an exploded view of the lens element parts and subassemblies. In Fig. 25, a complete miniature-sized wafer chip imaging system is shown alongside a conventional imaging system, both of which are suitable for use in portable devices such as mobile phones. What is so fascinating about this technology is that the whole imaging system of optics and sensor could be manufactured in one integrated process en masse in the same basic way as microprocessors, which should be highly cost effective. Also, one could imagine mobile phones using very

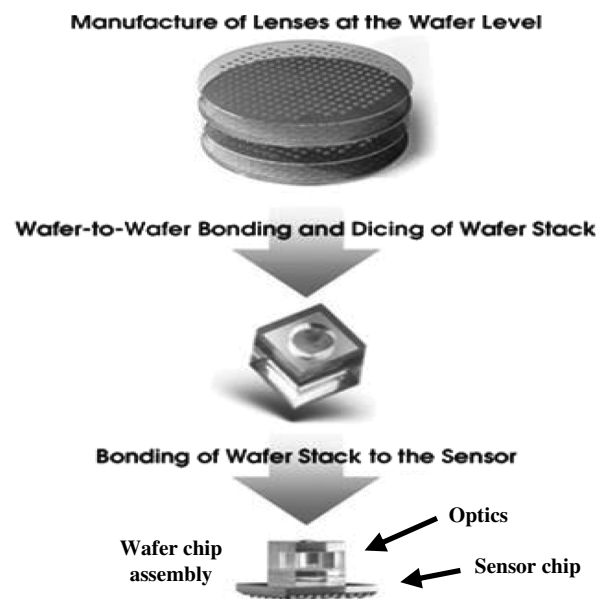


Fig. 23 Wafer chip fabrication.

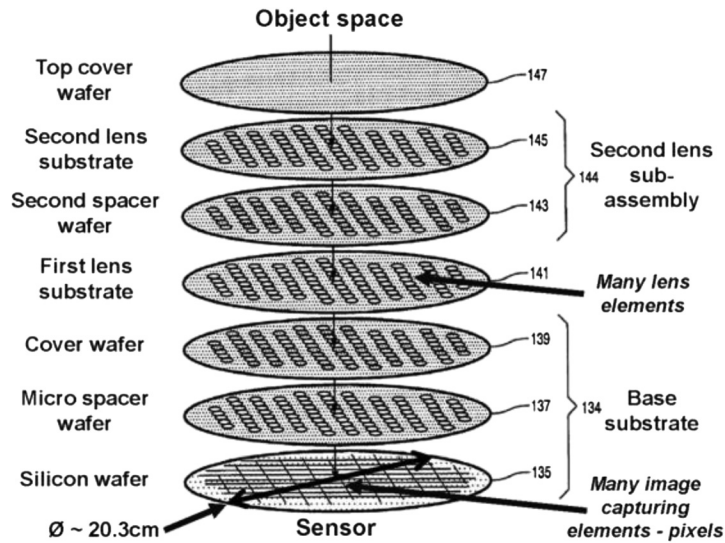


Fig. 24 Two lens element construction.

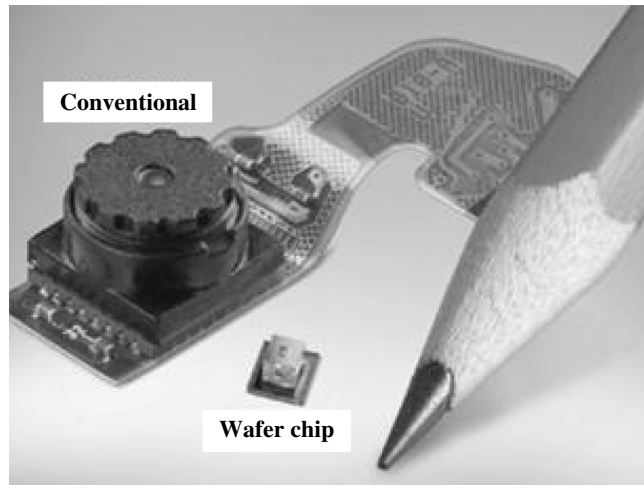


Fig. 25 Conventional versus wafer chip sensor package.

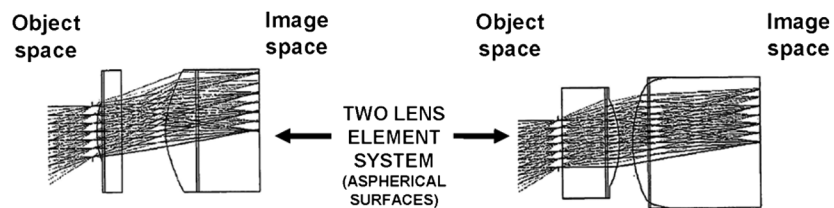


Fig. 26 Two lens element objective for wafer chip.

small imaging wafer chip systems of this kind multiple times to achieve results similar to those currently obtained with multiple, independent, and different sensors but offering even more versatility. It is difficult to predict where this technology might go, but one scenario is that it may be possible to replace the two conventional lens elements that form a prime lens,⁴¹ as displayed in Fig. 26, with the previously discussed liquid lenses to create a solid state zoom lens system that can have the lens shapes and powers electrically varied to provide focusing, zooming, thermal

compensation, and perhaps even stabilization functions. This may now sound far-fetched, but time will tell.

6.5 Computational Optics

Computational optics is another interesting technology that has recently been established to some extent and provides several functions.⁴² However, this technology is still in its infancy; therefore, time is needed to find out its capabilities. Nevertheless, there is no doubt that computational optics can be useful for manipulating images already captured, i.e., processing of post-captured images. From a zoom lens point of view, computational optics appears to have the capability to eliminate the need for zoom lenses altogether for certain kinds of imaging. For example, when at least two, although preferably more, prime lenses of different focal lengths capture several images at different magnifications or focal lengths and fields of view, the images can be zoomed in between by computation throughout a focal length range. In other words, a few images can be processed to provide many images that, when combined and viewed in a sequence, provide zooming but by computational zooming instead of optically. Another example involves taking two images of a scene generated by one focal length prime lens set at different focus distances and then using computational optics calculations to combine parts of the two scenes by superimposition; if more images are taken, then zooming parts of the scene can be mixed with parts that are not zoomed, thus providing an interesting resultant image that may not be readily produced by optical zooming alone. Both of these examples involve postcaptured images unlike real-time optically zoomed images in which the zoom lens optical design provides images continuously without postprocessing of the images. Of course, there may be ways to capture several images at one time and have computational zooming take place real time. It is hard to imagine where computational optics might go in the future, but for the moment it seems to be a parallel technology to zoom lens optical design that may augment optical zooming as opposed to entirely replacing it.

6.6 Artificial Intelligence

AI developments could also influence what happens to the optical design of zoom lenses. So far, AI in zoom lens optical design has been limited to the standard algorithms used in optical design software for optimization and tolerancing of optical designs. Global synthesis, genetic algorithms,⁴³ and deep learning algorithms and calculations⁴⁴ have all been tried with varying degrees of success. One of the interesting things about zoom lens optical design technology, or for that matter any kind of optical design technology, is that it comes in many forms. What one might wonder is, how do these techniques handle a situation such as choosing different technologies like using or not using liquid lenses? To be fully successful with zoom lens optical design, the aforementioned technologies appear to still have a considerable way to go even with ever faster computers, so this topic and zoom lens optical design warrants a separate paper in itself.

7 Summary

Optical design technology and manufacture has evolved over at least 100 years and continues to evolve. Early zoom lens optical design technology and manufacture was based almost entirely on finding rudimentary optical design solutions. The later advent of antireflection coatings and computer-aided optical design software enabled the creation of zoom lens optical designs of greater optical complexity with expanded specifications suitable for wider ranging applications. Further technological advancements in glasses, focusing lens arrangements, aspherical surfaces, movable irises, mechanical bearings for movable lens groups, and pupil control optics such as in compound zoom lenses have improved zoom lens optical design solutions to a level at which they compete very well with the best prime lenses for many if not most imaging characteristics and for many features. Future zoom lens optical design technology and manufacture is expected to continue the trend toward ever more sophisticated zoom lens optical design solutions, which should fulfill the ever-expanding needs of a myriad of imaging systems.

8 Conclusion

In the field of zoom lens optical design, many avenues have been explored and exhausted, yet many opportunities still exist. In the future, the evolution of zoom lens optical design will be further driven by advancements in optical design technology and manufacture. Diverse advancements may merge the imaging component chain including zoom lenses and sensors, thus producing more integrated forms of imaging system.

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