DE GRUYTER Adv. Opt. Techn. 2015; 4(1): 93–97

Tutorial

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The consequences of Petzval correction in lithographic designs

Abstract: Several design examples show how correcting Petzval curvature in high NA lithographic designs leads to much of the design complexity. There are two cases in which much simpler designs are possible, neither of them practical with today's technology. One is that of a curved object and/or image system, where no attempt at all is made to control Petzval curvature. The other case is where a diffractive surface is used in the design, which allows Petzval to be easily corrected in relatively simple designs. A very simple 1.1 NA all-refractive immersion design is shown that uses one diffractive surface.

Keywords: all-refractive immersion design; diffractive surface; high NA lithographic designs.

DOI 10.1515/aot-2014-0067
Received December 15, 2014; accepted January 12, 2015

1 Introduction

Suppose that we compare a variety of optical designs by looking at the sum of the absolute values of the surface curvatures. We can see by this means the effect of requiring very good aberration correction, including a very flat image surface. For this study here, we will only look at monochromatic designs, which simplify the design comparisons. The sum of the absolute values of the curvatures, for a given design focal length, is a good indicator of design complexity. A high value for this sum indicates either many lens surfaces, or some strong curvatures, or both. Since lithographic designs for the deep ultraviolet can only use low-index glasses like silica, which transmits at short wavelengths, we will assume just one glass type in these designs here with n=1.5. Let us start out comparing a single positive lens, with no aberration correction, with a focal length of 1.0 unit to a Cooke triplet design with the same focal length. The triplet design here is corrected to zero for the five third-order Seidel aberrations, unlike a ray optimized design. By making these aberrations zero, the field angle and design f# become irrelevant.

Figure 1A shows that the singlet lens has a sum of the absolute value of its curvatures of 2.0, while the Cooke triplet in Figure 1B has a sum of 17.4 – much larger. Now suppose that we correct for third-order spherical aberration, coma, and astigmatism but not Petzval curvature of the image. Then, the curvature sum can be driven done to 9.5 and that design is shown in Figure 1C. Almost half of the curvature sum of the Cooke triplet is, therefore, due to correcting Petzval curvature.

Designs that are corrected for a curved image can be much simpler and/or have better performance than designs that have to have a flat image. Figure 2 shows a 150-mm focal length monochromatic design that is f/1.0 and is diffraction limited at 0.5 μm over a 20° field, with no vignetting, on a curved image [1]. It would take many more lenses to get the same performance on a flat image. As it is not practical in today's lithographic systems to work with a curved image, this option is effectively closed off. But it is interesting to see how the design complexity changes when one or more of the normal ground rules of lithographic design are violated. A curved image lithographic design from my 2009 patent is shown in Figure 3. It has only 10 lenses, eight aspherics, and is 0.80 NA with a curved image object and a flat image. Its relative simplicity compared to flat image designs is due to the lack of Petzval correction.

2 Diffractive surfaces to correct for Petzval

A diffractive surface has no Petzval curvature of its own as shown by the high-index Sweatt model [2], but the

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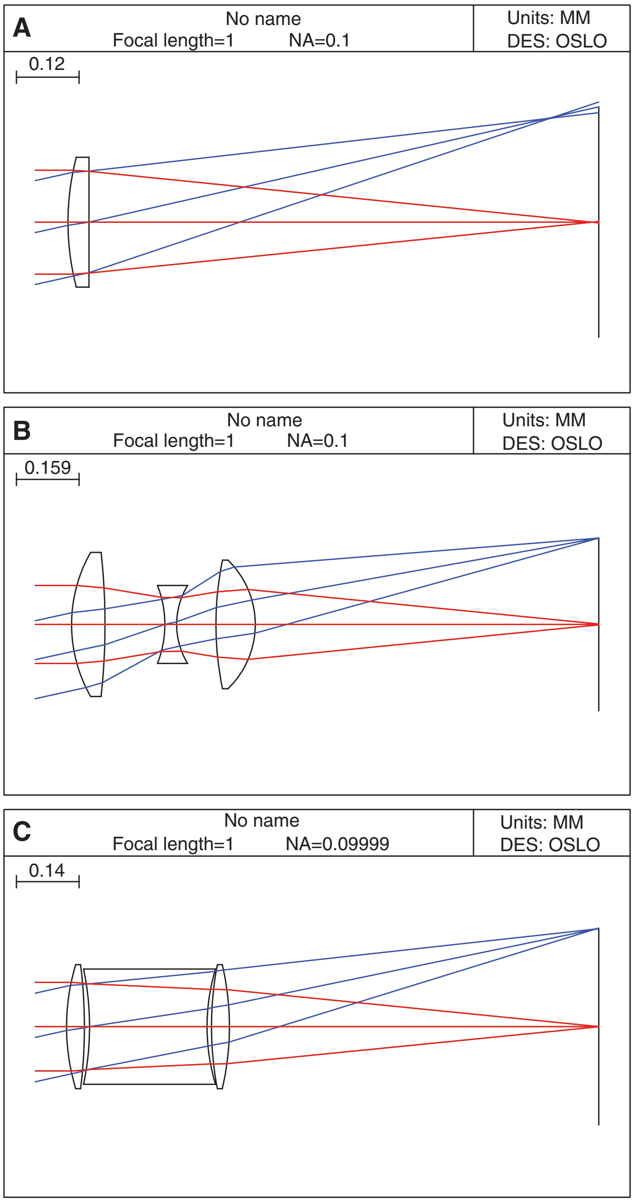

Figure 1 (A) Single lens with no aberration correction. Curvature sum=2. (B) Triplet corrected for five third-order aberrations. Curvature sum=17.4. (C) Petzval corrected is dropped. Curvature sum=9.5.

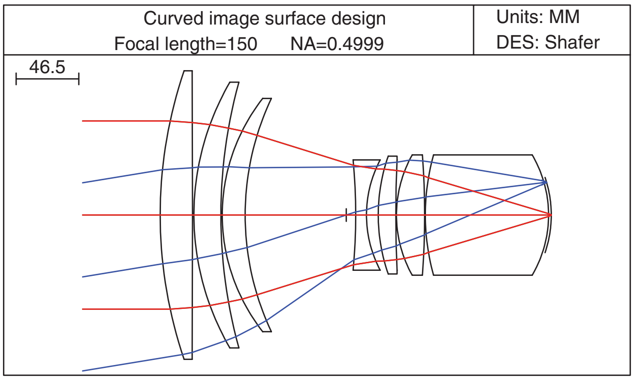

Figure 2 Curved image design, f/1.0, and 20° field.

substrate surface does – if it is curved. For simplicity, I am going to show some designs later where one or two diffractive surfaces are on flat silica substrate surfaces. Then that combined diffractive/refractive surface will have no Petzval curvature. But it will have power – diffractive power, but no refractive power (because of the flat surface), and it will have aberrations, except for Petzval. It is possible to make a high NA wide field-of-view design that only has diffractive surfaces, on curved substrates, where the glass substrate has no function except to hold up the diffractive surface [3]. Figure 4 shows an example of this. The diffractive surfaces here have both diffractive power and diffractive asphericity. A design like this is capable of very good performance at a fast speed and over a wide field of view.

For high NA lithographic designs, there is a requirement of a telecentric image, and the Figure 4 design is not suited for that. The extremely high performance of lithographic designs also takes many more design variables than are available in a simple system of a few aspheric diffractive surfaces. Figure 5 shows a typical example of a 4×0.70 NA, 26-mm field stepper lens for use at 0.193 unit. This is a 2003 Zeiss design from US patent 6,560,031. It has 30 lenses and one aspheric. The wavefront quality is about 0.005 waves r.m.s. over the whole field. As you can see, there is a very large number of design variables available for aberration correction. But these are pretty much all needed for the extremely good correction of high-order aberrations.

Using more aspherics allows a significant reduction in the number of lenses. Tenth-order aspheric terms on a surface have about the same number of variables as two lenses. The element sizes and weights can also be reduced by using many aspherics. The 0.90-NA design of Figure 6, a 2003 Zeiss design from US patent 6,646,718, is only possible with 30 lenses and 11 aspherics. The very high-order aberrations that occur at the 0.90-NA glass/air interface are very difficult to correct and require a lot of aspherics.

A different type of design results when you go to a high NA immersion system. There is no glass/air interface on the high NA immersion end so the aberrations are much smaller. But then, the system has a very high NA so that brings back some of the correction problems. There are some catadioptric immersion designs, not shown here [4] that use both lenses and mirrors, and the mirrors allow the system be corrected for Petzval in a way that is much easier than in an all refractive designs. Figure 7 shows a Zeiss patent from 2003, EP1485760A1 for a 1.1-NA all-refractive water immersion design. It has 25 lenses and

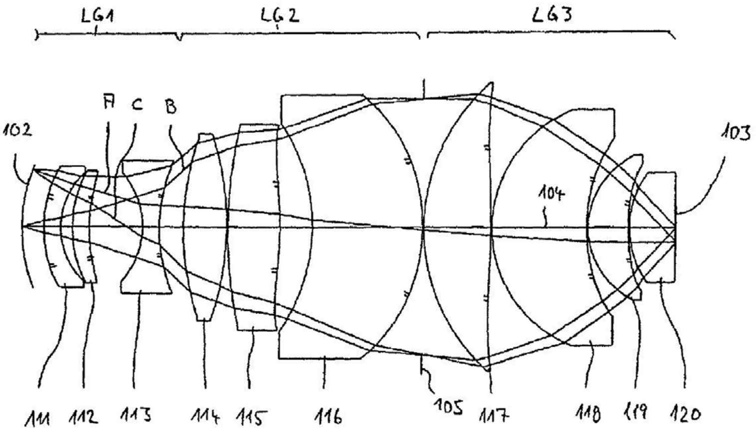

Figure 3 Curved object design, 0.80 NA at 0.193 unit. Many aspherics (US Patent United States Patent 7,511,890B2).

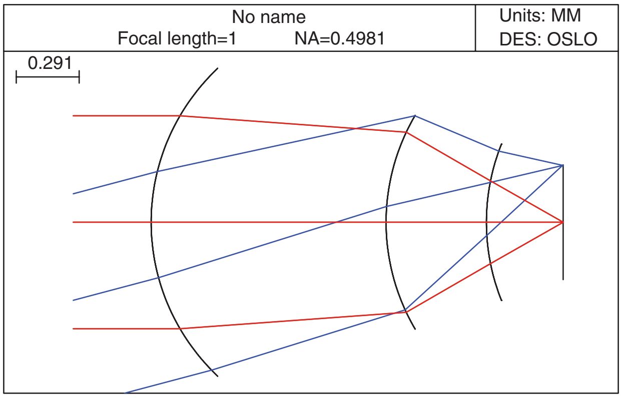

Figure 4 Three diffractive surfaces, no refractive power. Wide angle, fast speed.

six aspherics. The wavefront is about 0.005 waves r.m.s. at 0.248 unit wavelength. You can see that the design is almost solid glass from one end to the other. The length is about 1 m.

Now, for the interesting new designs. Suppose we combine a few aspheric lenses with one or two diffractive surfaces. The key idea here is to use the diffractive surfaces to put in a lot of positive power on a negative refractive lens. Then, it is possible to get a diffractive/refractive lens that has the desired Petzval correcting properties of a negative lens, but a net positive power due to the strong diffractive power. As a diffractive surface has no Petzval, we get all the benefit of the refractive negative power for correcting the system for Petzval. This can lead to some

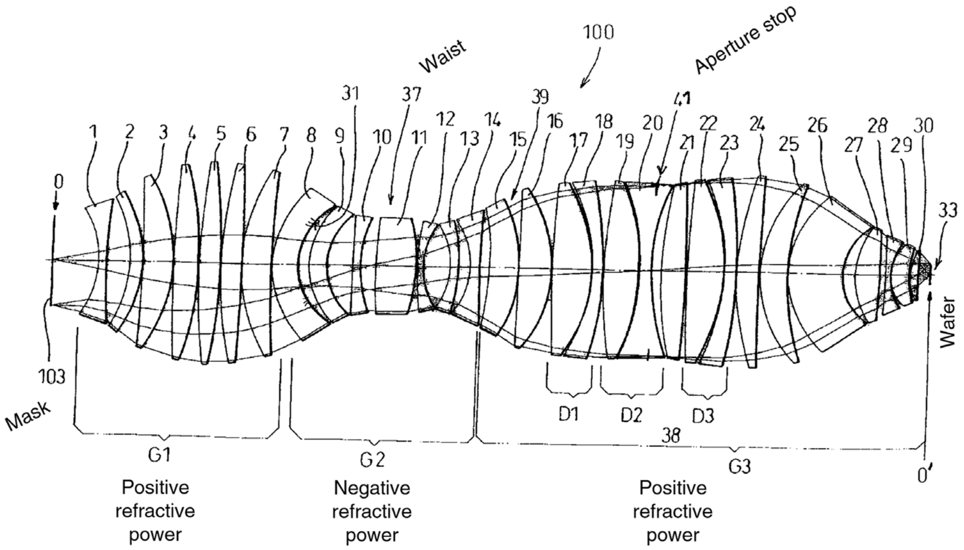

Figure 5 A 0.70-NA design, 30 lenses, one aspheric.

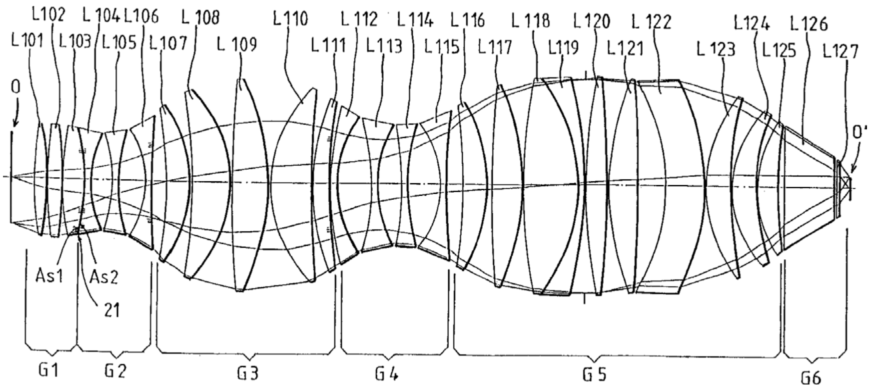

Figure 6 A 0.90-NA design, 30 lenses, 11 aspherics.

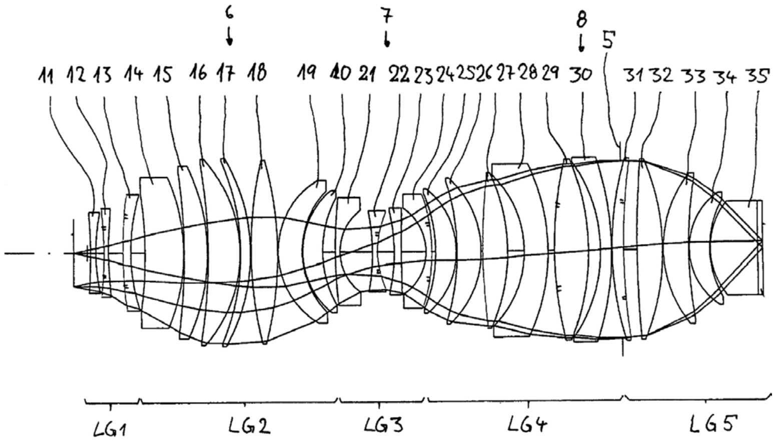

Figure 7 A 1.1-NA immersion design, 25 lenses, six aspherics.

strange looking ray paths. Figure 8, for example, shows a diffractive/refractive lens like this. It focuses light but clearly has the ‘wrong’ shape of a negative lens to do that. The strong diffractive power causes two problems – one is that the very small diffractive fringe spacing may easily exceed what is possible to make. The other is that it leads to an extremely small spectral bandwidth due to all the dispersion from the strong diffractive power.

Figure 9 shows a design with two diffractive surfaces. It is a 4× magnification 1.1 NA water immersion design with a 26-mm field size for use at 0.193 unit. The design is very much simpler than the complicated Figure 7 design

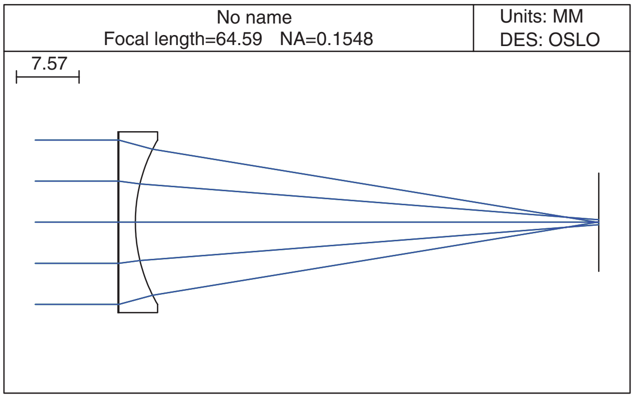

Figure 8 Diffractive/refractive element=positive power, negative lens Petzval.

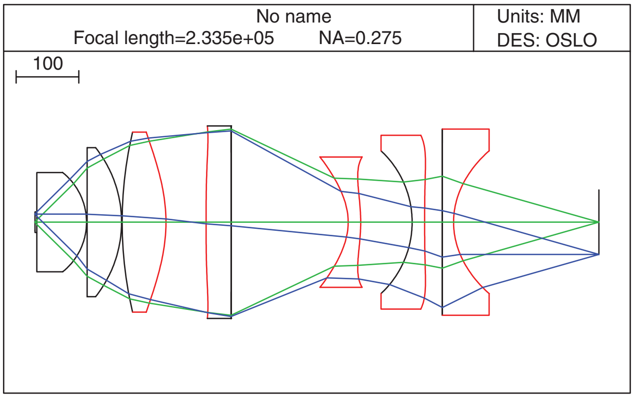

Figure 9 A 1.1-NA immersion lens, seven lenses, six aspherics, two diffractive surfaces.

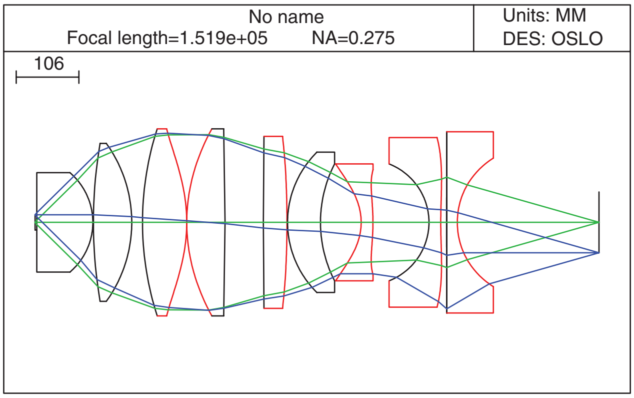

Figure 10 A 1.1-NA immersion lens, nine lenses, seven aspherics, one diffractive surface.

and yet has a similar performance. There are seven lenses, six aspherics, and two diffractive surfaces. Figure 10 shows a design with only one diffractive surface. It has two extra lenses and one extra aspheric and is about 0.010 waves r.m.s. over the 26-mm field. For this design, the worst ray deviation by the diffractive surface at the edge of the aperture and edge of the field is 86°. As the wavelength is 0.193 unit that means that the smallest diffractive fringe spacing is about 0.14 unit, and this is clearly not practical to make. The large amount of diffractive power on that element overwhelms the strong negative refractive power of the base lens, as can be seen by observing the ray paths going through the element. The result is a net positive power lens with negative Petzval aberration.

3 Conclusion

The use of a curved object or image surface or the use of a diffractive surface allows complicated high NA lithographic designs to be considerably simpler. That is because Petzval curvature is either ignored or is easily corrected by these means. Some examples show how much Petzval correction affects design complexity.

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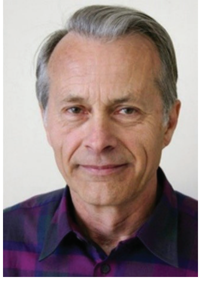

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