Optical design dependence on technology development

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ABSTRACT

Specific developments in optical technology over the past thirty years including refractive materials, thin film coatings and surface profiles will be discussed. A large variety of optical designs which depend on some of these developments will be described. The optical design examples presented will cover the infrared, visible, ultraviolet and combinations of these wavebands. A novel multi-waveband optical system that utilizes many of these developments will be illustrated in several possible configurations to meet different application requirements. A summary of the technologies employed in all of the optical design examples will indicate whether or not there may be trends in optical technology development. The optical design examples will be taken from issued Patents or published Patent applications and hence their optical prescriptions will be available for detailed analysis.

Keywords: optical design, technology, materials, coatings, surfaces, infrared, visible, ultraviolet, multi-waveband.

1. INTRODUCTION

To illustrate optical design dependence on technology development a variety of optical designs covering three decades have been selected from the Patent literature. Each optical design example is categorized by waveband of operation. The performance of the examples is not presented however all of the examples may be considered high performance for their intended applications. In general, the infrared waveband examples may be considered suitable for security type applications, the visible waveband examples are designed for consumer, prosumer and high end imaging applications, the ultraviolet waveband examples are specific to microlithographic applications and the multi-waveband examples may be appropriate for surveillance type applications.

Before commencing with the optical design examples the following definitions are given. Technology development is the progression over time of manufactured components which are materials (optical substrates), coatings (thin films) and surfaces (optical surface profiles). Optical design analysis and optimization software is a tool to apply the technology. The optical designer creates the optics portion of the optical system design by utilizing the optical design software to apply the technology. The object space is to the left and the image space is to the right unless otherwise specified, the field of view and numerical aperture are specified using the acronyms FOV and NA and the three wavebands together span a total wavelength range from 0.0134μm (13.4nm) to 13μm. After the section on examples a technology summary is presented, a couple of potential future technologies suggested and a broad conclusion drawn.

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2. EXAMPLES

2.1 Infrared waveband

The following examples show optical designs covering the 3-5µm and 8-13µm infrared waveband regions.

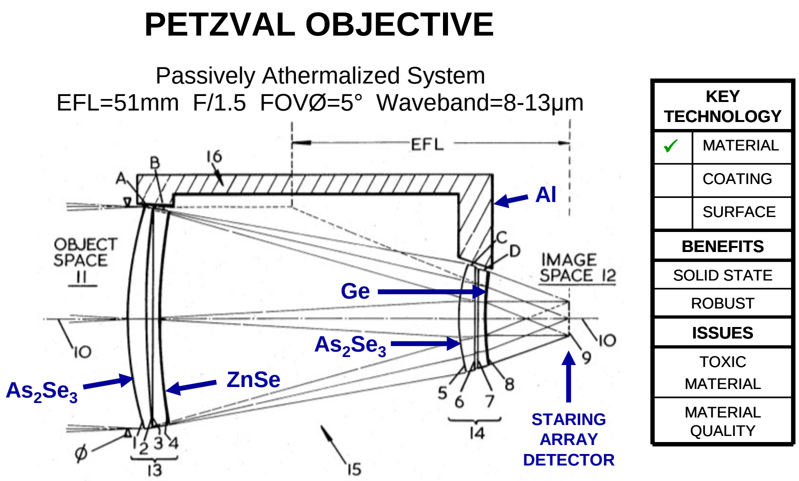


Figure 1

The first optical design example 1.1 shown in Figure 1 is a passively athermalized petzval objective for the 8-13µm infrared waveband region which is taken from a 1985 US Patent(1). Three different refractive materials are employed in four spherically surfaced lens elements which are supported in an aluminum structure. The dispersion and thermal change in refractive index of the refractive materials plus the thermal expansion of the aluminum facilitates an achromatized lens system which maintains high image quality over a temperature range from -40°C to +80°C (-40F to 176F). The key technology here is material.

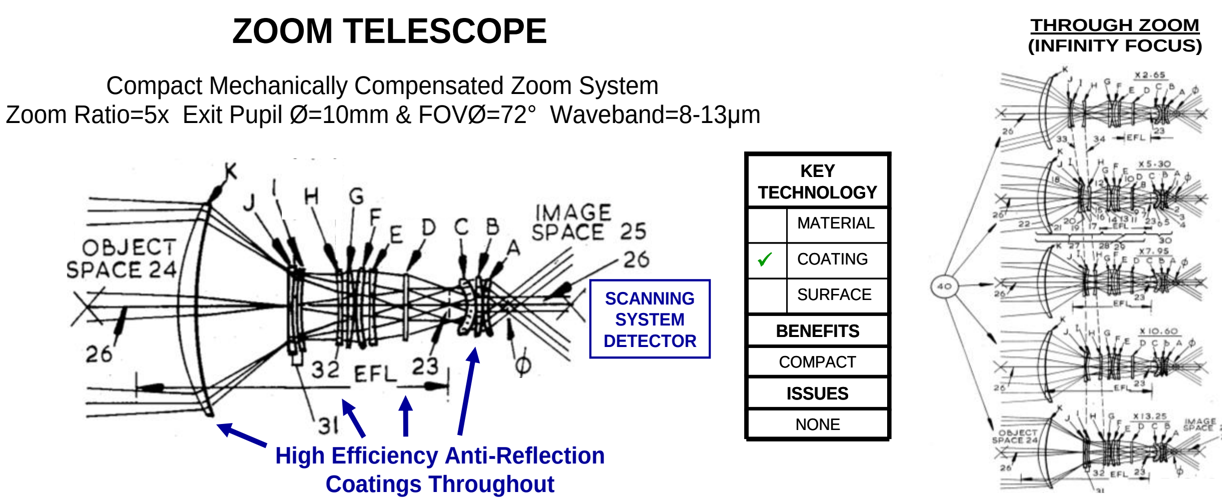


Figure 2

The second optical design example 1.2 illustrated in Figure 2 is a mechanically compensated afocal zoom telescope also for the 8-13µm infrared waveband region which is taken from a 1987 US Patent(2). One major difference between the previous example and this example is the increased total number of lens elements from four to eleven. Since refractive materials for the 8-13µm infrared waveband region typically exhibit high refractive indices from about 2 to 4, the total light loss from reflection may be substantial unless high efficiency anti-reflection coatings are used, e.g. about 60% transmission loss per uncoated lens element with a refractive index of four. The key technology here is coating.

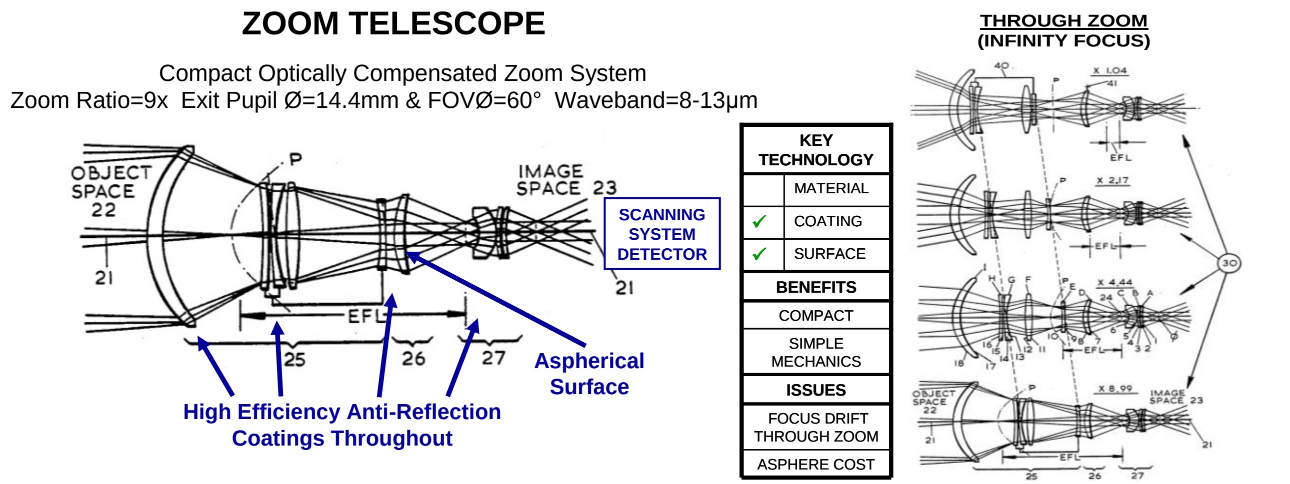


Figure 3

The third optical design example 1.3 depicted in Figure 3 is an optically compensated afocal zoom telescope again for the 8-13µm infrared waveband region which is taken from a 1986 US Patent[(3)]. This design uses two fewer lens elements than in the previous example but one lens element surface is aspherical in shape to maintain compactness. The key technologies here are coating and surface.

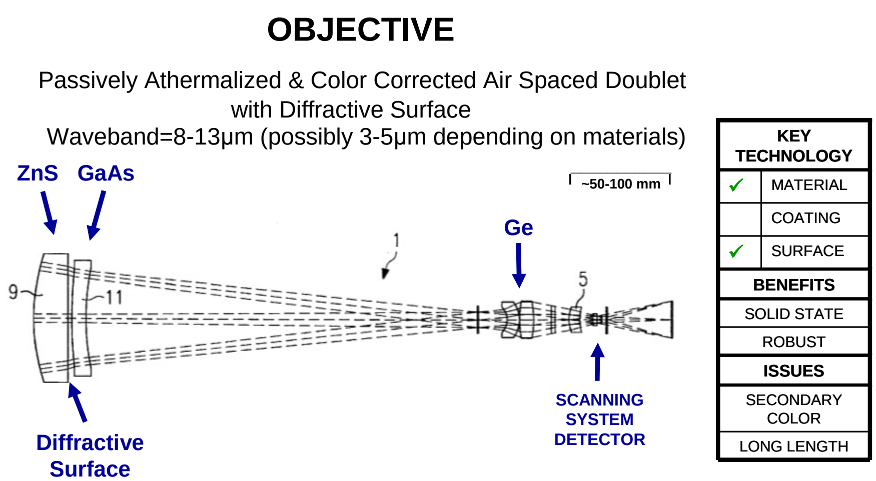


Figure 4

The fourth optical design example 1.4 portrayed in Figure 4 is an achromatized and passively athermalized objective for the 8-13µm infrared waveband region and possibly for the 3-5µm infrared waveband region after re-optimization, which is taken from a 1996 US Patent[(4)]. The different refractive materials in the air spaced doublet are utilized for their dispersive and thermal change in refractive index properties and are combined with a diffractive surface to achieve both the color correction and the thermal control. The key technologies here are material and surface.

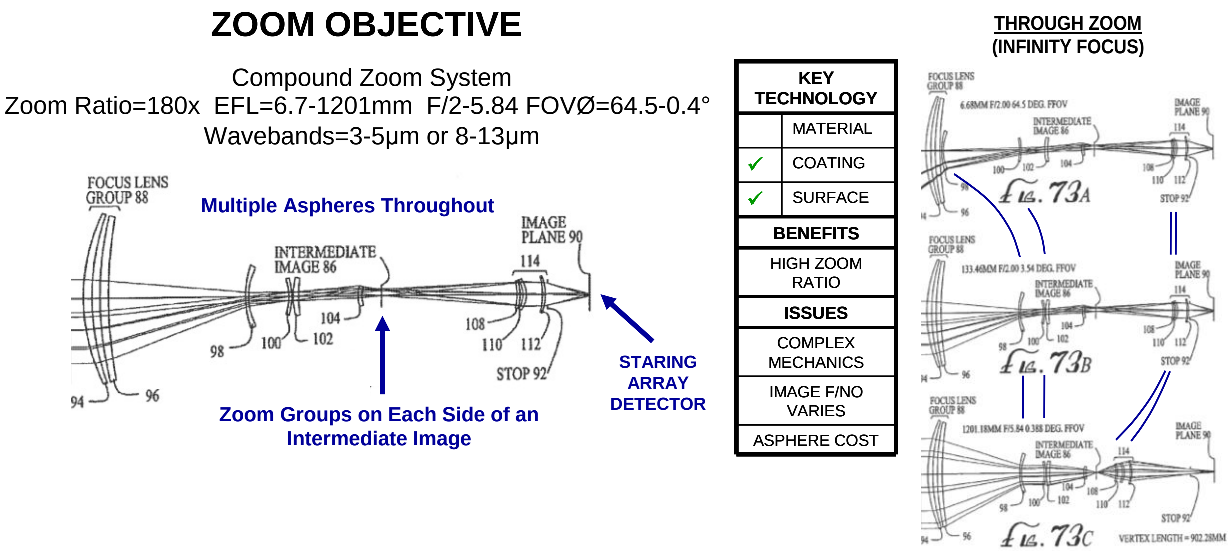


Figure 5

The fifth optical design example 1.5 shown in Figure 5 is an afocal zoom telescope for the 8-13µm infrared waveband region and possibly for the 3-5µm infrared waveband region after re-optimization, which is taken from a 2007 US Patent[5]. The compound zoom approach of having zoom groups separated by an intermediate image enables both a high zoom ratio and a fairly wide field of view to be achieved. However, the compound zoom approach may tend to require more lens elements. Therefore, multiple aspherical surfaces are used to provide the desired aberration correction. The key technologies here are coating and surface.

2.2 Visible waveband

The following examples show optical designs covering the visible waveband region.

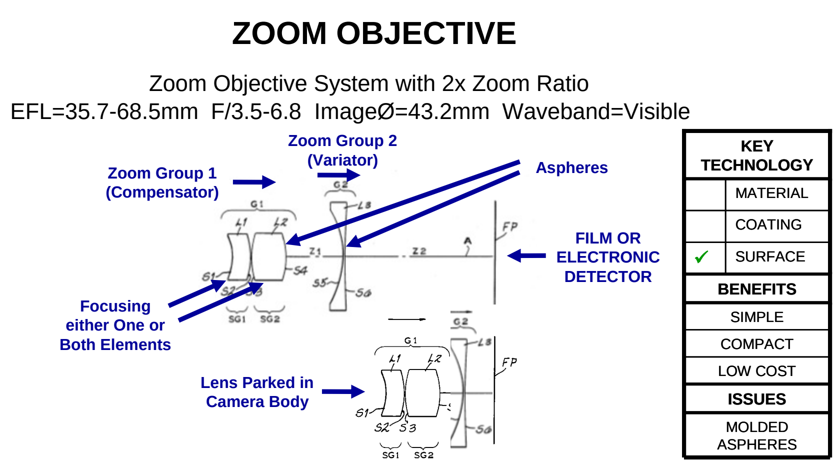
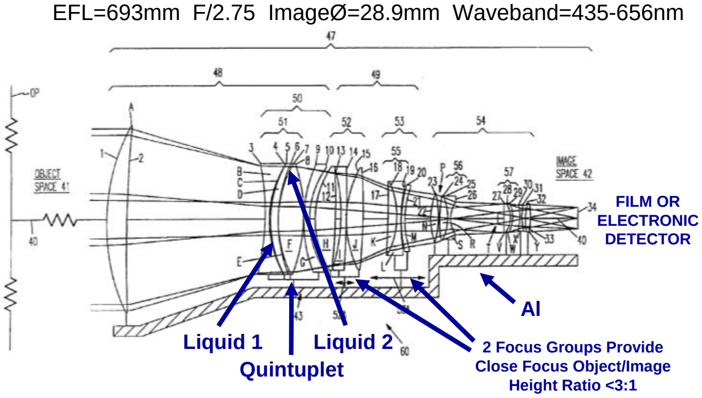


Figure 6

The first optical design example 2.1 for the visible waveband shown in Figure 6 is a zoom objective which is taken from a 1990 US Patent[6]. Even though the zoom ratio of 2x is small and the full aperture through zoom is slow the system is notable for its simplicity. The use of the two aspherical surfaces in the two zoom groups enables good aberration correction in a small package. The surface is the key technology.

TELEPHOTO OBJECTIVE

Passively Athermalized & Color Corrected System with Liquid Elements
EFL=693mm F/2.75 ImageØ=28.9mm Waveband=435-656nm



KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
LOW COST GLASSES	
COMPACT	
ISSUES	
LIQUID DISCOLORATION	
LOW TEMPERATURE	

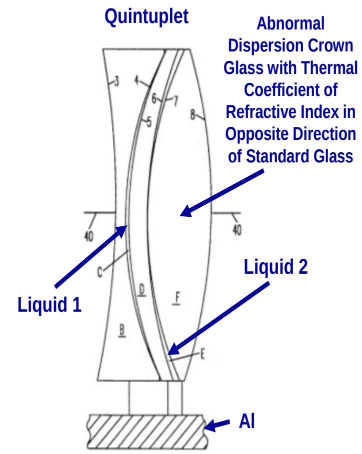
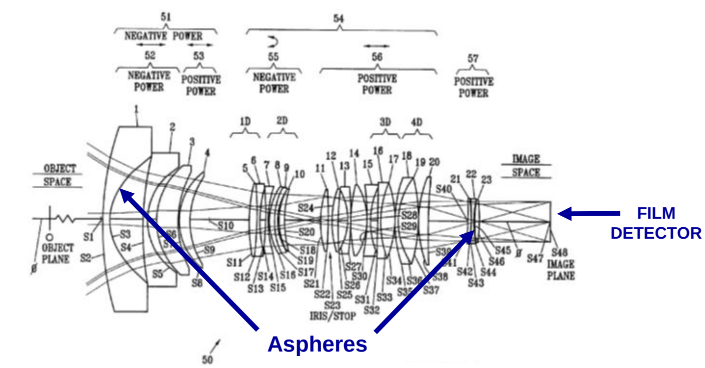


Figure 7

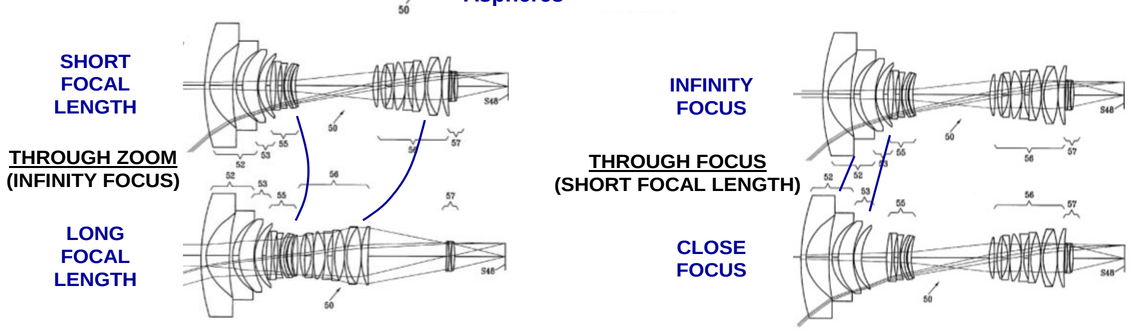
The second optical design example 2.2 for the visible waveband illustrated in Figure 7 is a passively athermalized and color corrected objective employing liquids which is taken from a 1997 US Patent[(7)]. Usually in fast aperture long focal length lens systems chromatic aberration correction may be costly because large diameter lens elements with abnormal dispersion glass types are required. To reduce the need for such glasses, a hybrid quintuplet lens group comprising two abnormal dispersion liquids and one abnormal dispersion glass is incorporated. The abnormal dispersion glass is used to compensate for a mismatch in thermal change in refractive index of the two liquids. Key technologies are material and coating.

ZOOM OBJECTIVE

Macro Focus Zoom System with 3.5x Zoom Ratio
EFL=14.5-50mm F/2.2 ImageØ=28.9mm Waveband=455-644nm



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
VERSATILE	
FIXED FOCAL LENGTH OPTION	
ISSUES	
COMPLEX MECHANICS	
ASPHERE COST	



Close Focus Object/Image Height Ratio = 2.5:1 (at Long Focal Length)

Figure 8

The third optical design example 2.3 for the visible waveband depicted in Figure 8 is a macro focus wide angle zoom objective which is taken from a 2000 US Patent[8]. Two aspherical surfaces are utilized, one distant from a pupil space and the other quite close to a pupil space, to correct aperture and field dependent aberrations. Particularly noteworthy is the fact that there is no simple and compact all spherical equivalent solution when the aspherical surface nearest object space is removed. Coatings are also important to maximize transmission given the large number of lens elements and the large ray angles at some of the lens element surface normals. Key technologies here are coating and surface.

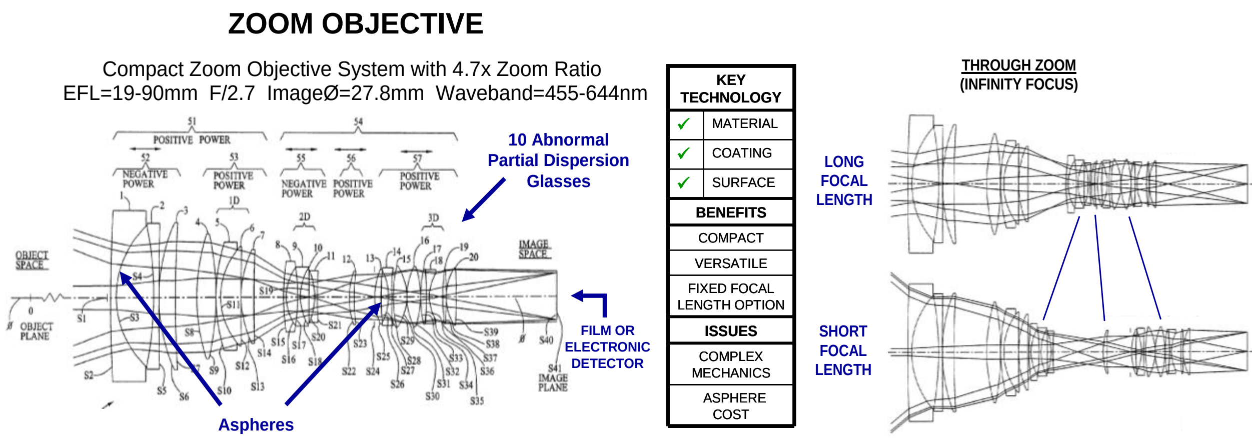


Figure 9

The fourth optical design example 2.4 for the visible waveband portrayed in Figure 9 is a zoom objective which is taken from a 2006 US Patent[9]. This system is similar in complexity to the previous example but has a larger zoom ratio of 4.7x, is less wide angle, is longer focal length and has a slightly slower aperture. This design relies on ten abnormal dispersion glasses for chromatic aberration correction. Key technologies are material, coating and surface.

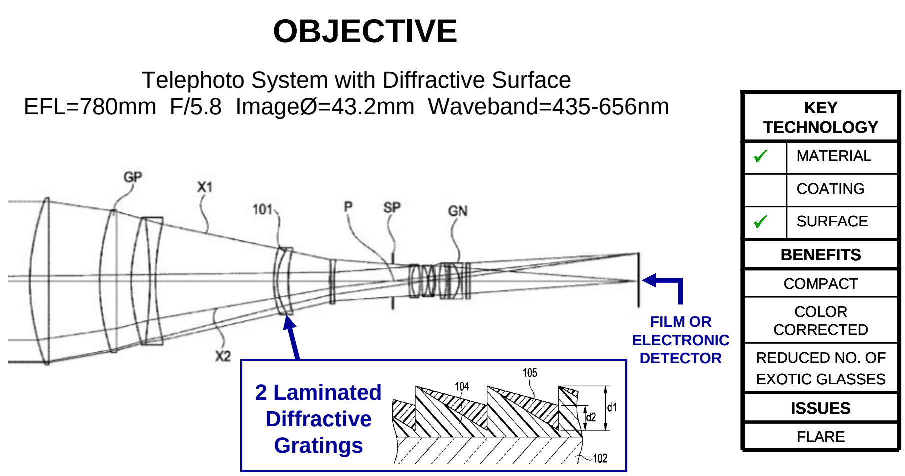
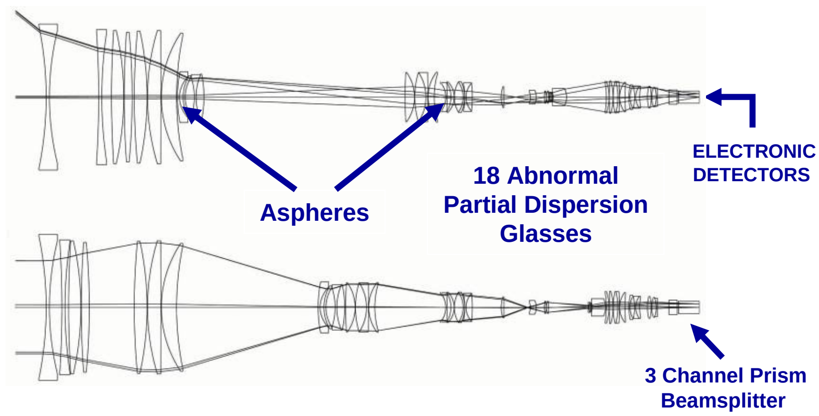


Figure 10

The fifth optical design example 2.5 for the visible waveband shown in Figure 10 is a telephoto objective employing a diffractive surface which is taken from a 2008 US Patent[10]. Unlike the previously described infrared waveband diffractive example 1.4, the diffractive surface in this system is likely to produce much more scattering at short wavelengths of operation. However, as in the earlier liquid lens example 2.2 one task is to reduce the number of costly abnormal dispersion glasses and possibly their corresponding weight. The laminated diffractive grating approach may be a good solution in those respects. Key technologies are material and surface.

ZOOM OBJECTIVE

Compound Zoom System with 300x Zoom Ratio
EFL=7-2100mm F/2-13 ImageØ=11mm Waveband=Visible



KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
LARGE ZOOM RATIO	
VERSATILE	
ISSUES	
COMPLEX MECHANICS	
ASPHERE COST	

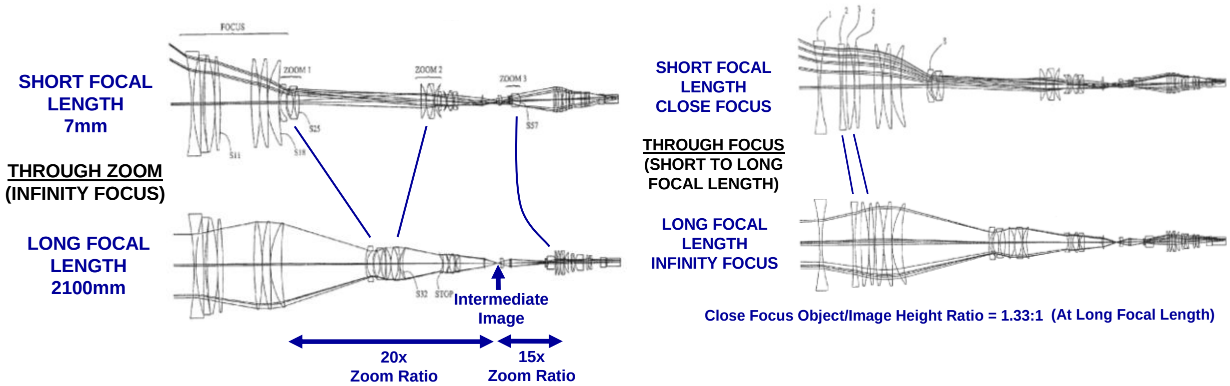


Figure 11

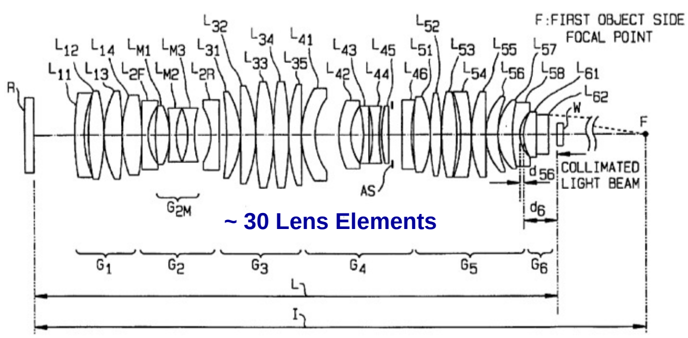
The last optical design example 2.6 for the visible waveband given in Figure 11 is a very large zoom ratio objective using a compound zoom approach which is taken from a 2005 US Patent[(11)]. The compound zoom approach mentioned earlier in example 1.5 may require a large number of lens elements and in this wide angle macro focus system, coatings are needed to minimize the transmission loss from thirty nine lens elements. Two aspherical surfaces and a multitude of abnormal dispersion glasses are utilized to provide the aberration correction. This lens system is about 1m (~3') in length and about 0.3m (~1') maximum diameter. Key technologies are material, coating and surface.

2.3 Ultraviolet waveband

The following examples show optical designs covering the ultraviolet waveband including the extreme ultraviolet soft x-ray wavelength of 13.4nm.

PROJECTION RELAY

All Refractive Projection System
RELAY=5:1 NA=0.57 ImageØ=31.2mm Wavelengths=193, 248 & 365nm



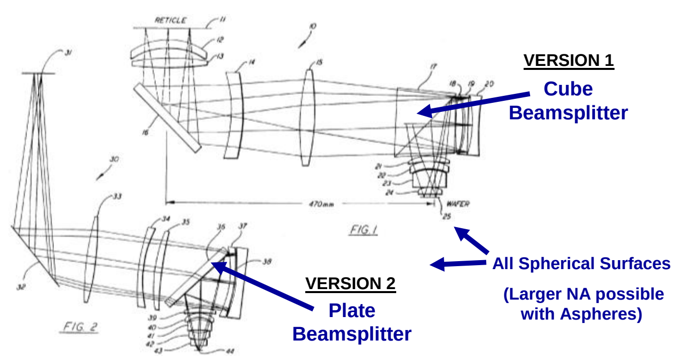
KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
RESOLUTION	
ISSUES	
INHOMOGENEITY & BIREFRINGENCE	
SURFACE QUALITY	
ALIGNMENT	

Figure 12

The first optical design example 3.1 for the ultraviolet waveband shown in Figure 12 is a twenty nine lens element all refractive relay taken from a 2002 US reissued Patent(12). Due to the large number of lens elements coatings are important to maximize transmission and the lens surface shapes need to be fabricated extremely accurately to realize the high resolution required at the short wavelength of operation. The key technologies are coating and surface.

PROJECTION RELAY

Refractive/Reflective Projection System
RELAY=4:1 NA=0.45 ImageØ=30mm Wavelengths=240-256nm



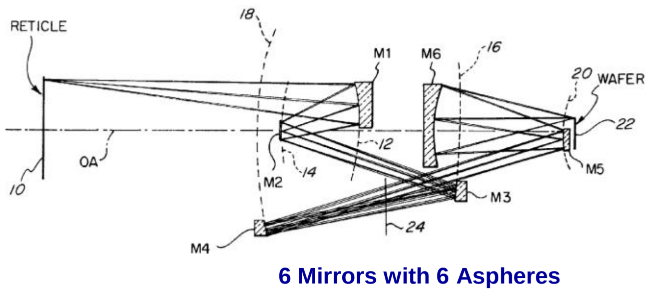
KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
RESOLUTION	
ISSUES	
ALIGNMENT	

Figure 13

The second optical design example 3.2 for the ultraviolet waveband illustrated in Figure 13 is a hybrid refractive and reflective relay taken from a 1990 US Patent(13). Compared to the last example this design has fewer lens elements and surfaces. However, a beamsplitter plus tilted and powered reflective surfaces require high quality materials and effective coatings. The key technologies are material and coating.

PROJECTION RELAY

All Reflective Projection System
RELAY=4:1 NA=0.25 ImageØ=31mm Wavelengths=13.4nm & <200nm



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
HIGH RESOLUTION	
ISSUES	
@13.4nm <10% TRANSMISSION WITH COATINGS	
ASPHERE COST	
ALIGNMENT	

Figure 14

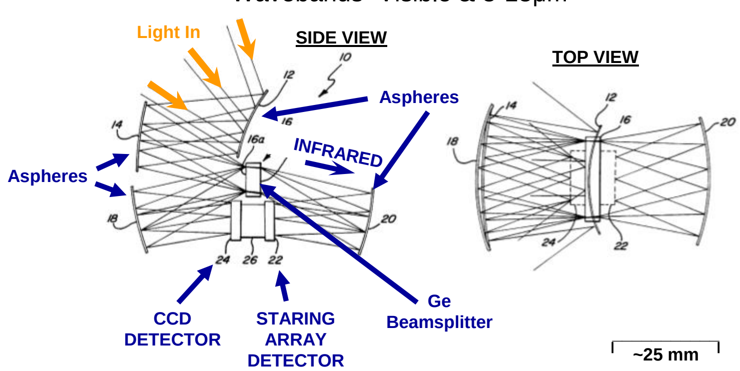
The last optical design example 3.3 for the ultraviolet waveband depicted in Figure 14 is an all reflective and all aspherically surfaced relay taken from a 1998 US Patent(14). For operation at the extreme ultraviolet soft x-ray wavelength of about 13.4nm special coatings are required even to provide a single surface reflection of about 70% and total system transmission of about 10%. Also, the surface shape accuracy needs to be superlative. The key technologies are coating and surface.

2.4 Multi-waveband

The following examples show optical designs covering several waveband regions, from the visible waveband through the 8-13µm infrared waveband region.

OBJECTIVE

Dual Waveband System
F/4.5(elev), F/1.5(azim) & F/2.3(average) FOVØ=40°(elev.) & 53°(azim.)
Wavebands=Visible & 8-13µm



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
COMPACT	
SOLID STATE	
ROBUST	
ISSUES	
ASPHERE COST	

Figure 15

The first multi-waveband optical design example 4.1 shown in Figure 15 is taken from a 1998 US Patent(15). The dual waveband system combines multiple aspherically surfaced reflective surfaces with a specially coated beamsplitter, to collect and direct the visible waveband and the 8-13µm infrared waveband region radiation to two detectors. The key technologies here are coating and surface.

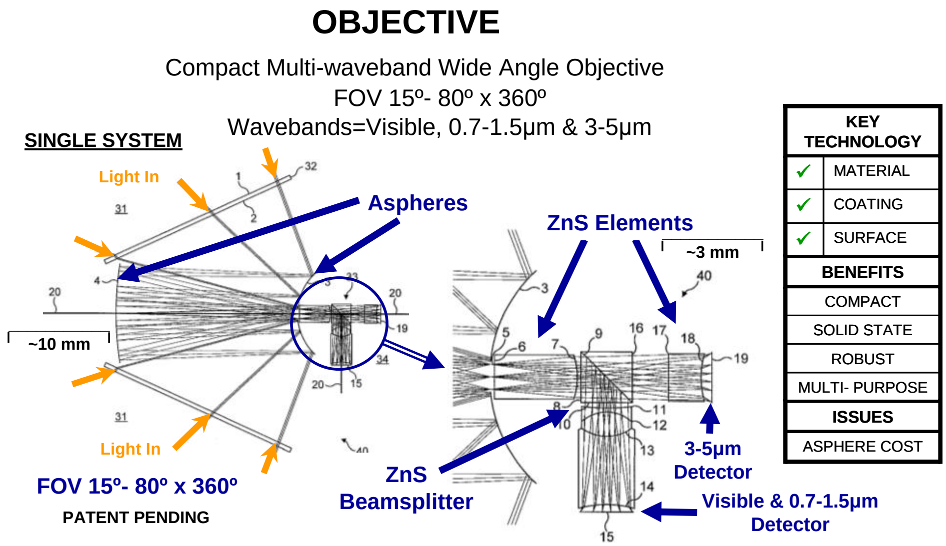


Figure 16a

The second multi-waveband optical design example 4.2 illustrated in Figure 16a is taken from a 2008 International Patent publication[16]. The system harnesses multi-waveband transmitting refractive material, a special beamsplitter coating and two aspherical reflective surfaces to collect and direct radiation to two detectors via a beamsplitter which separates the visible and near infrared radiation from the 3-5μm infrared waveband region. The triple waveband system forms two donut shaped images from a nearly hemispherical field of view and is approximately the size of a golf ball. However, there is a blind spot in the center of the field of view and this may be eliminated by reconfiguring the system. In Figure 16b it is shown that the blind spot may be replaced with two semi-circular blind spots at opposite sides of the periphery of the field of view. This is achieved by splitting the original system into a top section then placing two of these top sections back to back, thus creating an ‘igloo’ field of view.

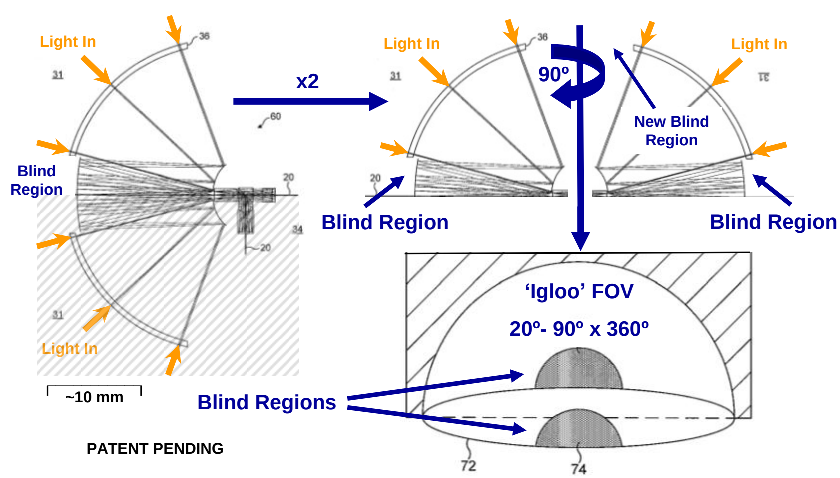


Figure 16b

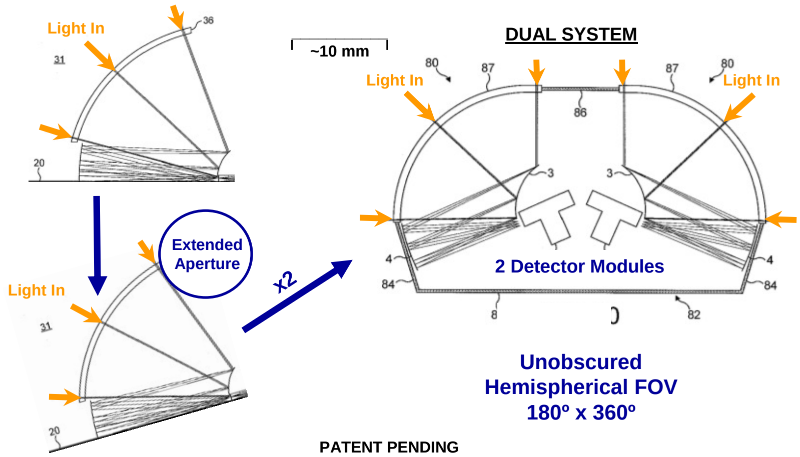


Figure 16c

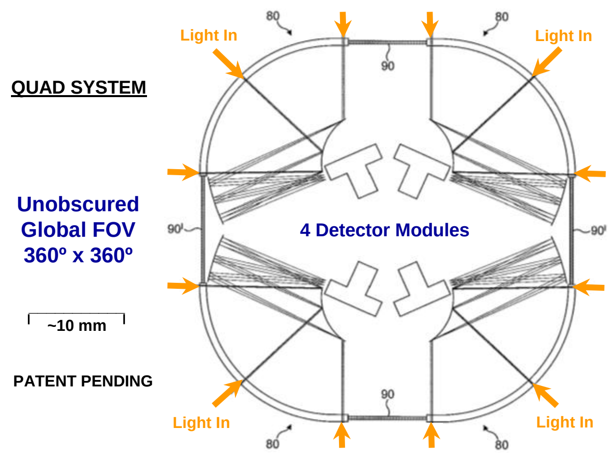


Figure 16d

As illustrated in Figure 16c a further refinement may be made to eliminate the two small blind spots by oppositely tilting both sides of the system and extending the upper fields of view. To provide an unobscured global field of view a second copy of the system may be inverted and placed below the original one thus producing a system that is about the size of a tennis ball (see Figure 16d). One downside to all of this reconfiguration is that many detectors are required and some of their images need to be stitched together. Introducing additional beamsplitters to combine different radiation paths may reduce the total number of detectors required but then the sensing of the images need to be shuttered. The image quality of these compact systems is driven more by the requirement for motion sensing rather than resolution. Higher resolution may be achieved by enlarging all of the systems. The key technologies in these systems are material, coating and surface.

3. SUMMARY

Figure 17 tabulates the various technologies employed versus waveband of operation and decade of occurrence, for the previously described examples. Even though the frequency of the technologies is example dependent the tabulation gives one cross section of what has happened over the last three decades.

	WAVEBAND															
	INFRARED					VISIBLE						ULTRAVIOLET			MULTI	
EXAMPLE	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	4.1	4.2
CIRCA	80's	80's	80's	90's	00's	90's	90's	00's	00's	00's	00's	90's	90's	90's	90's	00's
MATERIAL	✓			✓			✓		✓	✓	✓		✓			✓
COATING		✓	✓		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓
SURFACE			✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓

Figure 17

This paper has concentrated on the past; however, a brief mention will now be given about future technology development. Two technologies that may appear in future, or become more prevalent, fall into the technology categories of material and surface. The first potential technology is the variable power liquid lens cell which may augment or replace movable lens groups such as in zoom lenses. Variable power liquid lens cells may provide many significant benefits such as reduced mechanical complexity, lighter weight and possibly lower cost. A second potential technology is the free-form optical surface and improvements to the specification, optimization and tolerancing of aspheres, all of which may offer higher performance for existing and new optical designs.

4. CONCLUSION

Technology development usually provides optical design improvements but occasionally it is disruptive because it dramatically changes the direction of optical design advancement which may enable new optical design solutions that lead to highly competitive products. Two past examples of the latter are the dependence of multi element infrared zoom lenses on coatings for sufficient transmission and the dependence of high performance visible waveband zoom lenses on aspherical surfaces for compact packaging.

It is difficult to perceive any apparent trend in technology development, however, it may be said that “Necessity is the mother of invention” – Plato, c. 400BC.

5. ACKNOWLEDGMENTS

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