

Zemax OpticStudio Case Study: optical design of a finite conjugate, 4f, telecentric imaging system for re-imaging a VCSEL array

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Abstract

The performance of a 4f imaging system for a 7.75 mm x 7.75 mm VCSEL (vertical-cavity surface-emitting laser) array is investigated for different optical configurations and magnifications by consideration of the RMS spot radius and encircled energy plots in Zemax sequential mode. In general, off-the-shelf components are preferred due to the costly nature of manufacturing bespoke lenses. While in the case of [1:1] magnification, the use of an off-the-shelf achromatic doublet requires a small compromise on performance over the use of aspheric singlet, in the case of [1:1.25] magnification, it provides the best system performance. Additionally, the use of an achromatic doublet will make for a more robust system that can be used for a range of wavelengths of light.

1 Introduction

Zemax OpticStudio is an effective tool useful for aiding the design of an optical system. It can be used to identify the best material for the optical components in a system, along with their dimensions and the overall layout. Component materials can also be evaluated based on factors such as robustness and cost. The first step is to input an initial design based on the design specification. The tolerances of the design specification can then be numerically expressed in terms of the ‘merit function’. The rest of the optical design process is an iterative procedure with the ultimate goal of optimising the system such that the value of the merit function is reduced to zero. In this case, the aim is to design and analyse four different telecentric, 4f systems, for imaging a 7.75 mm x 7.75 mm VCSEL (vertical-cavity surface-emitting laser) array for both [1:1] and [1:1.25] paraxial magnifications according to a given design specification. In this report, Zemax OpticStudio (version 20.1) is used to create designs for telescopes with: equiconvex singlets, biconvex singlets, aspheric singlets and cemented achromatic doublets from the Thorlabs catalogue. Models for each of the different scenarios are available upon request. The performance of these various systems is presented and compared.

2 Initial Design

To begin setting up the design in Zemax, information about the ‘object’ to be imaged is required. In this case, the object is a 32 x 32 VCSEL array emitting at a wavelength of 980 nm. The

parameters Zemax requires for such a finite conjugate system in object space are summarised in Table 1. These will remain the same for all cases discussed in this report.

While the laser array measures 7.75 mm x 7.75 mm, the beam in Zemax is a circular beam and so a beam diameter of 11.0 mm is required to encompass the square size of the array. This maximum diameter determines the values of the three field positions that will be used to optimise the system and are chosen using the ‘Fields Wizard’ in the ‘Field Data Editor’. The ‘Equal-area Y Fields’ distribution option selects values weighted towards the maximum value. This should help to evenly optimise the system since aberrations get increasingly worse as the field position becomes further off-axis. In addition, a telecentric object space is used to accurately represent the VCSEL array and an additional ‘clear semi-diameter margin’ of 5 mm is included to avoid the beam from clipping the optics when mounted.

Numerical aperture in object space	0.18
Maximum object height [mm]	11.0
Field positions [mm]	0, 3.9, 5.5

Table 1: Summary of parameters required to accurately describe the VCSEL array in Zemax.

Once the object parameters have been determined and accurately setup in Zemax, the initial design of a simple 4f system can be built in Zemax based on the given design specification. In this case, there are four different optical configurations for each of the two magnifications. The specification of all the singlets in the [1:1] magnification case have the same basic specifications, these are summarised in Table 2. In the [1:1.25] magnification case, only the first singlet has the design specification given in Table 2. The second lens in all of the different setups will instead have an effective focal length of 100 mm but all other specifications remain the same as in Table 2. Implementation of the initial design of the four different optical configurations are discussed in the following sections.

Effective focal length [mm]	80 ± 2
Lens diameter [mm]	< 60
Lens thickness [mm]	< 30
Schott glass material	N-BK7 or N-BAF4

Table 2: Summary of singlet specifications used as the first lens in all optical configurations.

2.1 Equiconvex Singlets

To create an equiconvex lens, use a pickup on the radius and diameter of the rear surface of the lens from the front surface. To create two identical equiconvex lenses, use pickups on the radii, diameters and thickness of the second lens from the corresponding surfaces on the first lens.

2.2 Biconvex Singlets

To create a biconvex lens, remove the pickup on the radius of the rear surface from the front surface used in the equiconvex case. To create two identical biconvex lenses, use pickups on the radii, diameters and thickness of the second lens from the first lens. However, ensure that the front surface of the second lens is picked up from the rear surface of the first lens with a scale factor of -1 to ensure the lenses mirror each other.

2.3 Aspheric Singlets

To create an aspheric lens, the 'Find Best Asphere' function in the 'Optimisation Tools' tab can be used. To create two identical aspheric lenses, change the 'Surface Type' of the corresponding surface on the second lens in the 'Lens Data Editor' from 'Standard' to 'Even Asphere'. Again, ensure that if the asphere is on the front surface of the first lens that the pick up creates the second asphere on the rear surface of the second lens and vice versa. Then the '2nd Order', '4th Order', e.t.c. terms can be made to pickup values from the first lens with a negative scale factor.

2.4 Imported Cemented Achromatic Doublet

To import a Thorlabs cemented achromatic doublet with specifications equivalent to the singlets in the previous cases, use the 'Lens Catalogue' in the 'Stock Parts' section of the 'Libraries' tab. To create two identical imported lenses, import a second identical lens and make sure to select the 'Change Sign of Surface Geometry in Mirror Space' option to reverse the surfaces such that the two singlets mirror each other. Additionally, the shortcut 'Ctrl'+ 'Shift'+ 'B' can be used to reverse the surfaces once the lens has been imported.

3 Optimisation Strategy

Once the initial designs have been implemented in Zemax, the optimisation process can begin. In order to perform an optimisation of the system, Zemax requires information on which parameters are allowed to vary and by how much. There are two parts to achieving this: (1) defining an end goal for Zemax to work towards through various operands in the 'Merit Function Editor' and (2) telling Zemax which parameters are variables in the 'Lens Data Editor'. In this case, the latter is achieved by simply making the 'Radius' and 'Thickness' of all the surfaces, that are not already defined as pickups, a variable, except for in the case of imported components as their dimensions are fixed. The first step, however, is slightly more complicated as it involves setting up a merit function. This is discussed in more detail throughout this section.

3.1 Merit Function

A combination of merit function operands are required to create a robust, yet flexible 4f system, that can be, locally or globally, optimised for different requirements. Additionally, operands can be given a weight, which, at first will be given a value of one. Then, after an initial optimisation, the value of this weight for each parameter can be adjusted and the system re-optimised. This can help improve performance if the result from the initial optimisation is unacceptable.

In the following sections, the main basic commands that can be input into the merit function to achieve this are discussed, along with two optional commands that are not essential for the operation of the merit function but will help to monitor and control the performance of the system. Once the merit function has been setup, a local optimisation can be performed using the 'Optimize!' function in the 'Automatic Optimization' section of the 'Optimize' tab. A global optimisation can also be ran to improve performance by escaping local minima. This is done with the 'Hammer Current' function in the 'Global Optimizers' tab.

3.1.1 Paraxial Magnification, 'PMAG'

The 'PMAG' command is used to set the desired magnification of the entire system. This operand will have a value of -1 for the [1:1] case and -1.25 for the [1:1.25] case. The values are negative

because the image of the VCSEL array will be inverted. Additionally, the greater than, ‘OPGT’, and less than, ‘OPLT’, operands can be used in conjunction with the ‘PMAG’ operand in order to set the 1 % tolerance on the magnification set out in the specification.

3.1.2 Effective Focal Length, ‘EFLY’

The ‘EFLY’ operand is used to specify the target effective focal length of a lens. In the [1:1] case, this operand will have a value of 80 mm and is only required once as the second lens will pickup the required effective focal length from the first lens. However, in the [1:1.25] case, two ‘EFLY’ operands are required, one with a value of 80 mm and the second with a value of 100 mm. No ‘EFLY’ operand is used for the cemented achromatic doublet as the imported lens parameters are fixed. Again, the greater than, ‘OPGT’, and less than, ‘OPLT’, operands can be used in conjunction with ‘EFLY’ to set the ± 2 mm tolerance on the focal length, as specified in Table 2.

3.1.3 Total Inclusive Thickness, ‘TTHI’

The ‘TTHI’ operand is used to define the total inclusive thickness between two specified surfaces. This can be used to define the total track length of the entire system. The ‘TTHI’ operand will have a value of 350 mm \pm 100 mm according to the design specification. Again, this tolerance can be set with the greater than, ‘OPGT’, and less than, ‘OPLT’, operands.

3.1.4 Real Ray Angle of Incidence, ‘RAID’

The ‘RAID’ operand has two particular uses in the 4f system. The first is to ensure that the rays between the two lenses are collimated. The second is to create telecentric output operation.

This operand works by defining the angle at which a particular ray in the system sits at a certain surface. For collimated operation, this is achieved by setting the angle of incidence of the marginal ray to zero degrees at the ‘STOP’ surface. For telecentric operation, the angle of the chief ray, for the off-axis fields, are set to zero degrees at the ‘IMAGE’ surface.

3.1.5 Real Ray y-coordinate, ‘REAY’

The ‘REAY’ operand is used to ensure that the ‘STOP’ surface is located correctly between the two lenses in this 4f system. This operand works by defining the height at which a particular ray in the system should be at for a certain surface. Correct positioning of the ‘STOP’ surface is achieved by setting the height of the chief ray of all three fields to zero at the ‘STOP’ surface.

3.1.6 Diameter Less Than, ‘DMLT’ (optional)

While use of all the above operands will achieve a merit function suitable for the required task, additional operands can also be useful. The ‘DMLT’ operand is used to ensure that the diameter of a surface is less than a specified value. In this case, it will ensure that the restrictions on the lens diameter, given in Table 2, are met.

3.1.7 Relative Glass Cost, ‘GCOS’ (optional)

Another additional operand, the ‘GCOS’ operand, can be used to improve the performance of the merit function when it is desirable to take cost considerations into account. This is particularly useful when using material substitution from a glass catalogue (discussed further in Section 3.2) during optimisation. In this case, ‘GCOS’ is used to influence the optical design based on the relative cost of the glass material, as given in the glass catalogue.

3.2 Material Substitution

Further optimisation is achieved through a glass substitution to compare the performance of different materials. Pre-existing glass catalogues can be used to tell Zemax the available substitute glasses or a bespoke catalogue can be made to specify a group of chosen glasses in the ‘Materials Catalogue’ in the ‘Optical Materials’ section of the ‘Libraries’ tab. The ‘Substitute’ parameter solve on the material needs to be selected along with the name of the desired catalogue. An optimisation can then be run with the ‘Automatic’ optimisation option in the ‘Hammer Current’ optimiser. This calls the local optimiser to cycle through the different glasses in a specified catalogue.

4 Results and Performance Analysis

4.1 [1:1] Magnification

The resulting optimised layout of the different optical configurations, for the [1:1] magnification case, are shown in Figures 1 a-d. The optical designs all have total track lengths between 320 mm and 350 mm, lens diameters around 45.0 mm (allowing for the use of standard 2” optics) and magnifications with the tolerance of $\pm 1\%$, specified in the design specification. Individual values for these, in each optical configuration, are given in Figures 1 a-d along with lens focal lengths, which all lie within the specified tolerance range detailed in Table 2.

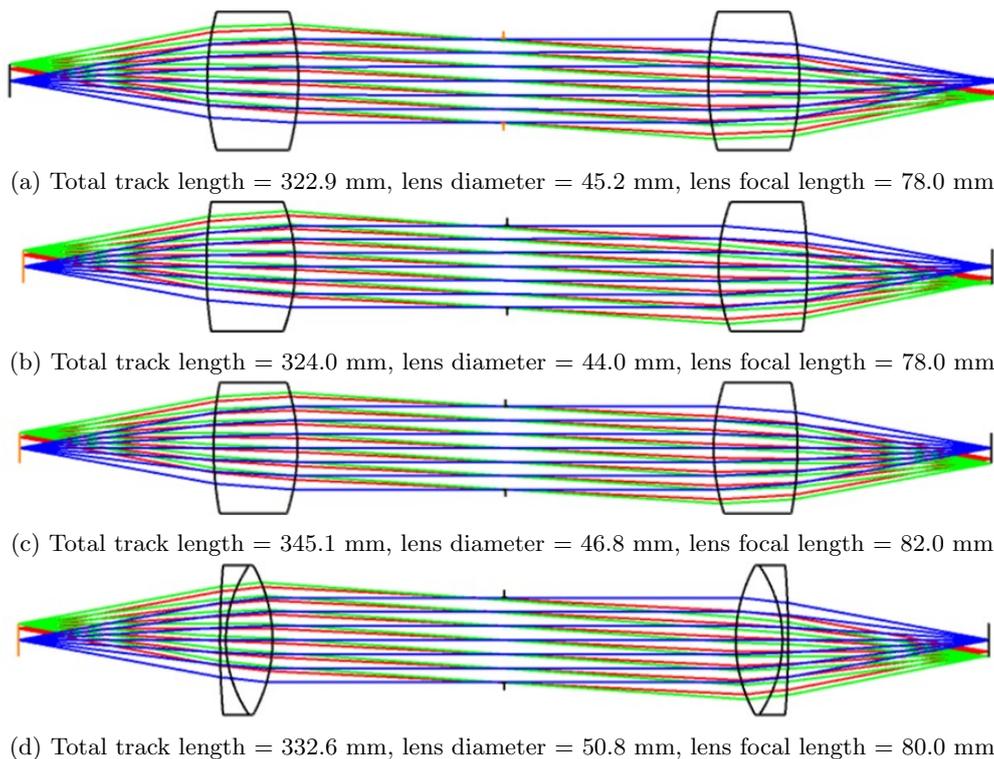


Figure 1: Layout of an optimised telecentric, 4f imaging system for two identical (a) equiconvex, (b) biconvex, (c) aspheric singlets and (d) Thorlabs cemented achromatic doublets.

The ‘Find Best Asphere’ function found the rear surface of the first lens to be optimal and so a corresponding aspheric surface was placed on the front surface of the last lens. The material substitution optimisation resulted in the use of the N-BK7 Schott glass in all cases, as it has a lower relative cost. Without the use of the ‘GCOS’ operand, the material substitution optimisation resulted in the use of the higher relative cost material, N-BAF4 Schott glass, in all cases.

One method of evaluating the performance of each system is through the geometrical RMS spot size at the image plane. The spot diagrams for all three field positions and for each optical configuration are shown in Figure 2 to allow for a direct comparison between the cases. It is worth noting that the scales vary in this figure between different optical configurations. The large scaling difference observed in Figure 2 is depicted more clearly in Figure 3 a.

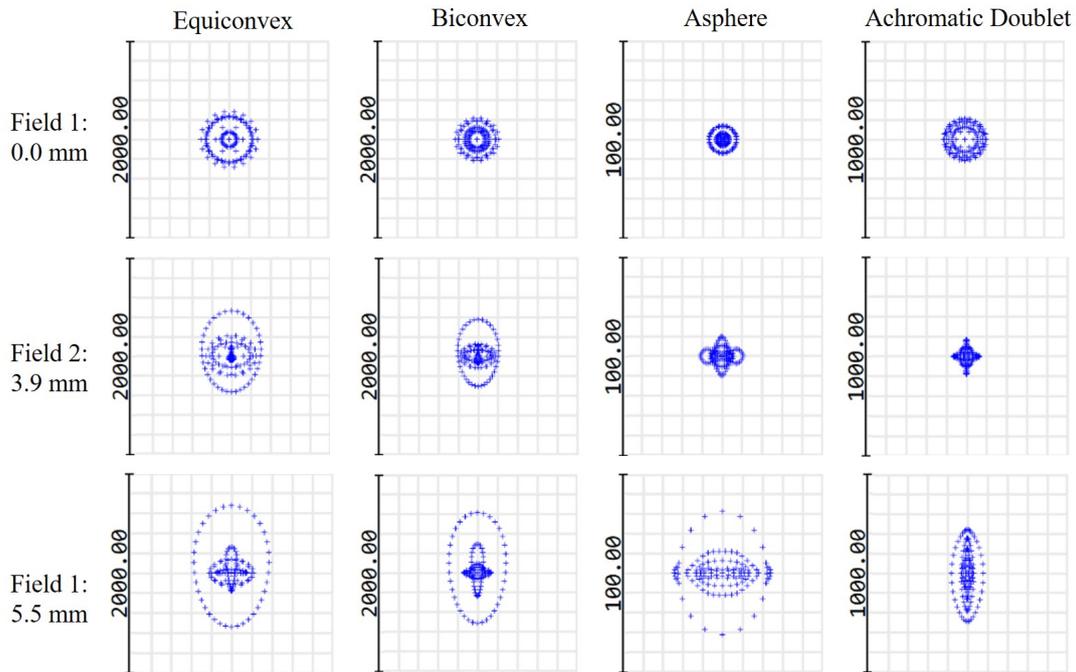


Figure 2: Geometrical spot diagrams for four [1:1] magnification cases and three field positions: 0 mm, 3.9 mm and 5.5 mm, used to optimise the systems. *Note: scales vary between cases.*

The optimised optical configurations for the first three cases, or the bespoke, identical singlet cases, all have the smallest and most symmetrical spot size when the field position is on-axis, while performance is seen to deteriorate with an increasingly off-axis field position. This is expected due to various aberrations that are introduced when the beam is off-axis. However, the off-the-shelf Thorlabs cemented, achromatic doublet is seen to perform better for the off-axis field, at 3.9 mm, than for the on-axis field position. This behaviour could be explained due to the fact that the dimensions of the off-the-shelf components are fixed. This could mean that when an optimisation is run, Zemax has to sacrifice the performance of the on-axis beam in order to minimise the overall merit function.

While performance comparison of the different optical systems in Figure 3 a is analysed by considering the behaviour of the RMS spot size, the performance of optical systems can also be compared by considering geometric encircled energy plots. Encircled energy plots indicate how

the power of the beam is spread out in order to give a measure of brightness in the central lobe and, therefore, how much power is lost to the fringes. Figure 3 b shows a chart summarising the behaviour of the systems, in terms of the encircled energy, for comparison. In particular, the radius for which 80 % of the encircled energy occurs has been plotted for each field position in each case. In all cases, the spots have fringes that become increasingly spread out as the field position becomes more off-axis. All cases, apart from the aspheric surface, for the field at 3.9 mm have the smallest amount of power in the fringes. This is because aspheric surfaces are designed to remove spherical aberrations.

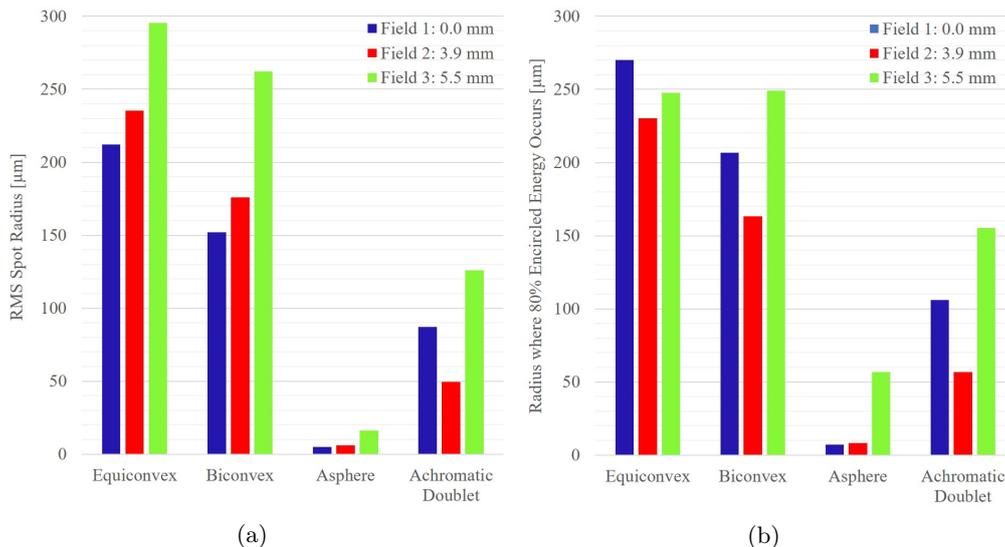


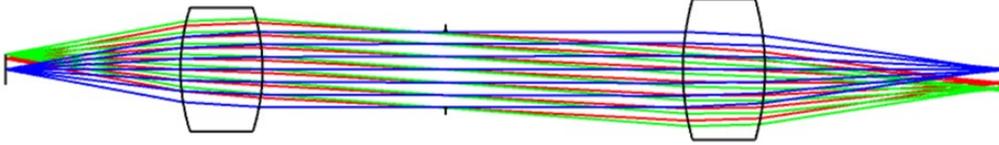
Figure 3: (a) RMS spot radius and (b) radius where 80 % of encircled energy occurs for all four [1:1] magnification cases and all three field positions: 0 mm, 3.9 mm and 5.5 mm.

Overall, the first case, with two identical equiconvex singlets, is the most simple 4f system to implement. However, it is the most restricted system in terms of variables and, as a result, has the worst performance out of all the cases, with the largest spot sizes and fringes. The second case, with two identical biconvex singlets, has a slightly improved performance over the first case with marginally smaller spot sizes and fringes. This is due to the extra variable made available by allowing the radius of curvatures of the two surfaces of the singlet to vary independently of each other. However, the most significant improvement in performance is seen in the third case through the addition of an aspheric surface to the rear surface of the first lens and front surface of the second lens. The aspheric surface is seen to vastly improve the performance of the system, both on- and off-axis, with the smallest spot sizes and the smallest beam power in the fringes.

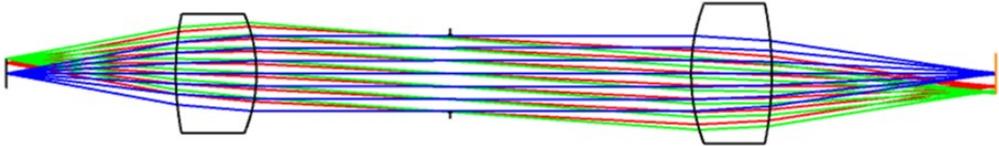
4.2 [1:1.25] Magnification

The resulting layout of the different optical configurations, for the [1:1.25] magnification case, are shown in Figures 4 a-d. The optical designs all have total track lengths between 360 mm and 390 mm and lens diameters around 45 mm for the first lens and less than 60 mm for the second lens. Individual values for these, in each optical configuration, are given in Figures 4 a-d along with lens focal lengths and system magnifications, which all lie within the specified tolerance range detailed in the design specification.

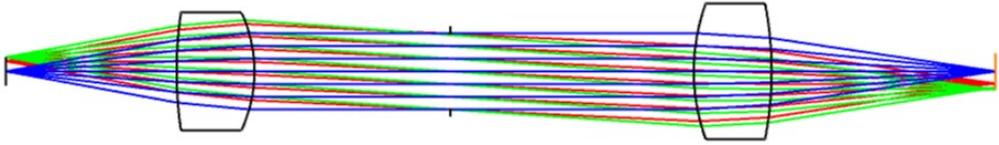
For the third case at this magnification, the design specification requires that only one surface of the two lenses are allowed to be replaced with an aspheric surface. Again, the Find Best Asphere' function found the rear surface of the first lens to be optimal. The material substitution optimisation again resulted in the use of the N-BK7 Schott glass in all cases. Without the use of the 'GCOS' operand, the material substitution optimisation resulted in the use of N-BAF4 Schott glass, in all cases apart from the standard lens in the aspheric case.



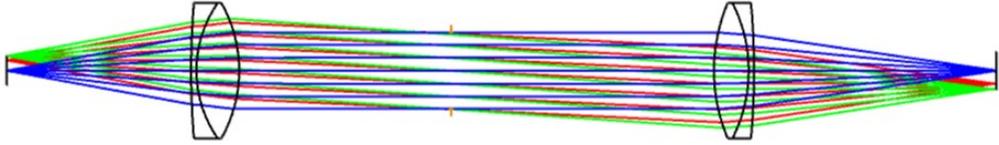
(a) Total track length = 364.2 mm, first lens diameter = 45.2 mm, second lens diameter = 51.2 mm, first lens focal length = 78.0 mm, last lens focal length = 98.0 mm, system magnification = -1.257.



(b) Total track length = 366.9 mm, first lens diameter = 44.4 mm, second lens diameter = 52.0 mm, first lens focal length = 79.1 mm, last lens focal length = 98.0 mm, system magnification = -1.240.



(c) Total track length = 381.6 mm, first lens diameter = 45.4 mm, second lens diameter = 52.4 mm, first lens focal length = 80.9 mm, last lens focal length = 102.0 mm, system magnification = -1.260.



(d) Total track length = 370.7 mm, first lens diameter = 50.8 mm, second lens diameter = 50.8 mm, first lens focal length = 80.0 mm, last lens focal length = 100.0 mm, system magnification = -1.246.

Figure 4: Layout of optimised optical configurations for (a) two equiconvex singlets, (b) two biconvex singlets, (c) one aspheric and one biconvex singlet and (d) Thorlabs cemented achromatic doublets, forming a telecentric, 4f imaging system.

In some cases, the initial optimisation of the system, with a weighting of one for each operand in the merit function, did not produce an optical configuration with the magnification within the required tolerance. Therefore, a larger weighting had to be applied to drive it to within the acceptable range. The weights of the other operands can also be varied to achieve a better performance at the cost of other operand performances depending on the desired outcome of the optimisation.

The same performance evaluation from Section 4.1, was applied to the spot diagrams and encircled energy plots for all cases in the [1:1.25] magnification. The charts for the spot diagrams and encircled energy are given in Figures 5(a) and (b), respectively. The same general behaviour for the different fields is observed as before, however, for this case the achromatic doublet appears to have the best overall performance with the smallest spot sizes and fringes.

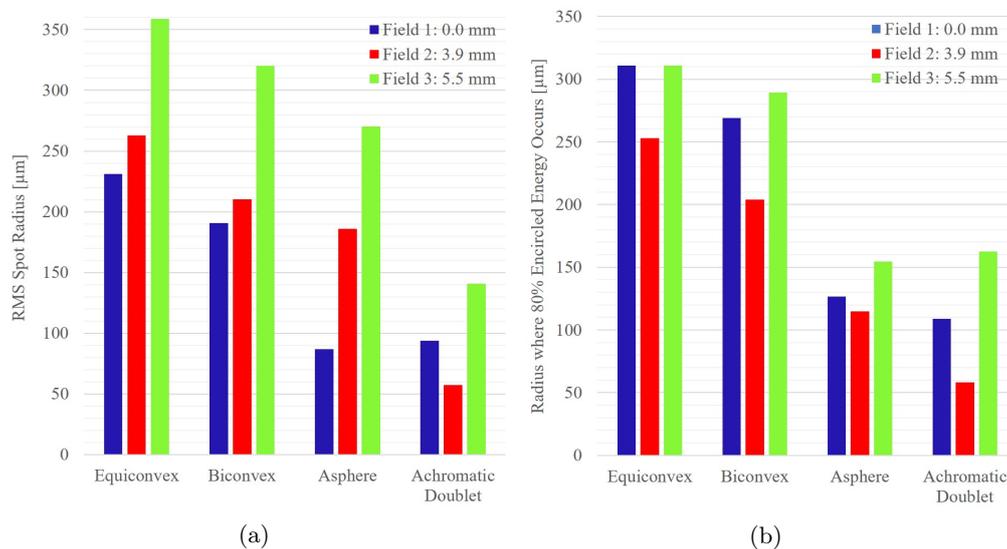


Figure 5: (a) RMS spot radius and (b) radius where 80 % of encircled energy occurs for all four [1:1.25] magnification cases and all three field positions: 0 mm, 3.9 mm and 5.5 mm.

5 Summary

While the third case for the [1:1] magnification case appears to have the best overall optical performance, it is also worth considering the ease of procurement of the optics involved. In the first three cases for both magnifications, the optics required all have bespoke values that might be quite difficult to procure. Therefore, the fourth case, that has been optimised using a Thorlabs off-the-shelf component, may be a preferable alternative as it is readily available to purchase, and even has the best performance in the [1:1.25] magnification case. This makes procurement of system components much easier and cheaper. The replacement of the singlet with doublets also makes this system more robust and transferable such that it can be used for different wavelengths of light. Alternatively, if the nature of the system requires an optical configuration with optimal performance, and procurement costs and lead times are not an issue, then the aspheric singlets may be worth considering for the [1:1] magnification case.