

# Application of Global Optimization to Design of an Aspheric Pickup Head for Multiple Wavelengths

Chao-Hsi Tsao\* and Jyh-Long Chern\*\*

Department of Photonics, Institute of Electro-Optical Engineering  
Microelectronics and Information System Research Center  
National Chiao Tung University, Hsinchu 300, Taiwan  
email: \*[chaohsi.eo92g@nctu.edu.tw](mailto:chaohsi.eo92g@nctu.edu.tw) \*\*[jlchern@faculty.nctu.edu.tw](mailto:jlchern@faculty.nctu.edu.tw)

## ABSTRACT

An optimization process combining of global optimization algorithm and further optimization treatment is proposed and demonstrated with application to the objective lenses of multiple-wavelength configurations. Based on the optimal variable set of aspheric coefficients obtained by the proposed global optimization strategy, singlet objective lens for different operational configurations, i.e., for CD and DVD, and for DVD and HDDVD, can be deduced.

**Keywords:** optimization, objective lens, optical design

## 1. INTRODUCTION

Typically, the design space of optical systems is a multidimensional parameter space which constructs a very complicated value space of merit function determined by the required performance. By searching within whole region of parameter space it is possible to yield the best solution or, at least, the acceptable designs so that the desired requirements can be fulfilled. However, it takes inestimable time to penetrate through the entire high dimensional design space to find the best solution even the most powerful computer is utilized. In order to efficiently and effectively grab local minima in the merit space, a lot of algorithms have been purposed since tens years ago. Among these algorithms, the most popular optimization routine which can be widely accepted is Damped Least Square (DLS) method or other gradient-dependent algorithms related to DLS [1]. Despite this kind of algorithms based on the systematic descent principle are effective and efficient in some applications especially for a linear system, however, they are not able to, in general, find the best solution universally and they easily get trapped in a particular local minimum where has been probably determined by the initial location. Thus, a non-local, even a global, searching algorithm is necessary to handle the increasingly growing need of the application of optical design in the future. A lot of global optimization algorithms have been proposed to compromise the computational effort and effectiveness in finding the best solution in design space, which include deterministic and probabilistic algorithms [2]. The deterministic algorithms find the global minimum by some exhaustive search of the design domain without any stochastic process involved, but on the contrary, random sampling is the key process for the probabilistic algorithms by which they can approach the global minimum. In this paper, we proposed a searching scheme combining of random process and an adaptive topographic roam algorithm to achieve the purpose of global optimization.

In order to verify the capability and feasibility of our proposed algorithm, it is worthwhile to look over the objective lens design for the optical pickup apparatus which plays a very important role in the modern storage applications, especially for the higher storage density has been demanded in there years with the attention on high definition television are increasing. To have the highest storage density, the spot size focused by the objective lens is ideally approaching to the diffraction limit governed by the Rayleigh limit, which states that either shorter wavelength or larger numerical aperture (NA) will reduce the size of the focused spot. Hence the working wavelength have been deduced gradually from 0.78 $\mu$ m, 0.65 $\mu$ m to 0.405 $\mu$ m for the compact disc (CD), digital versatile disc (DVD) to high density DVD (HDDVD) respectively, and the NA has been heaved from 0.47 to 0.65 for the needs of higher standards. Owing to the backward compatibility, a newer standard has been considered to be able to access the older standard. Separated optical devices for different working wavelengths are the simplest way to solve the compatibility issue, however that will

increase the cost, the difficulty of mechanical design and the physical size of the pickup head. Thus a single design of objective lens for multiple configurations is a useful and low-cost solution for the application of optical storage.

For the extreme performance of an objective lens, spherical aberration free and the lowest wavefront error are necessary criteria. However, a spherical lens is not able to achieve those requirements with larger NA system. To overcome this issue, non-spherical lens elements are the potential candidates of the solutions. With the advancement of manufacturing technology, aspheric lens is no longer to be an unsolved issue in fabrication. Naturally, a singlet lens with aspheric surfaces will be taken as a solution of the design of optical pickup head. We may use two aspheric surfaces to ensure the attainment of aplanatism. Wasserman and Wolf proposed a method to obtain two first-order simultaneous differential equations for solving the profiles of two adjacent aspheric surfaces [3]. By which, a singlet aspheric lens can be numerically determined for ideal imaging with the smallest spot size and least in optical path difference. But the situation becomes more complicated for a singlet objective lens working with multiple wavelengths.

For the designs of objective lens for multiple configurations, polarized holographic optical element [4], a catadioptric lens with a dichroic mirror [5] and diffractive optical elements (DOE) [6-7] have been proposed to solve the compatibility problem. Among those proposals, DOE has been paid a lot of attentions in working for the Blu-ray and DVD since it can serve for the CD/DVD compatible system [6-7]. On the other hand, aspheric lens or complex surfaces lens is not a critical issue in lens fabrication due to the progress of fabricating technology. Using aspheric lens to correct the image aberration, and even more, to find an appropriate set of aspheric coefficients for multiple configurations is commercially possible. However, multiple wavelengths, and even multiple configurations will make the problem much complicated since the dispersion of lens material and too many different requirements are involved. Undoubtedly, global optimization would be a very useful tool for searching a suitable solution for variety of wavelengths and specifications.

Thus in this paper, we utilized the proposed global optimization scheme to give assistance of designing two singlet aspheric objective lenses for CD and DVD, and for DVD and HDDVD with nearly diffraction limit performances.

## 2. PROPOSED GLOBAL OPTIMIZATION SCHEME

The downhill simplex method proposed by Nelder and Mead [4] is popular and it may frequently be recognized as one of the best method for optimal solution approaching without derivatives evaluation in  $N$  dimensional space. The downhill simplex method works out by its geometrical naturalness rather than the mathematic derivatives and this feature makes it suitable for optimization of optical system design due to the relation between variables and objective function is not in close form. Through the geometrical movements, such as reflection, expansion, contraction and shrinkage [8], the simplex will finally approach to a minimum value. Indeed, the downhill simplex method is one of the local optimization algorithms if the characteristic length scales for each vector direction were fixed, as following equation mentioned in chapter 10.4 of Numerical Recipe in C [9].

$$\vec{P}_i = \vec{P}_o + \lambda_i e_i, \quad (1)$$

where  $e_i$ 's are the  $N$  unit vectors,  $\vec{P}_o$  is the initial point,  $\vec{P}_i$  represents the other  $N$  points among  $N + 1$  points, and  $\lambda_i$  denotes the characteristic length scale for each vector direction.

However, if the  $N + 1$  points were chose randomly within a particular range which encloses the starting point rather than the fixed characteristic length scale, the path by which it converges to a local minimum will be different depending on the stochastic initial vertices especially for truly high dimensional design space and complicated merit space. The downhill direction and path would be determined stochastically due to the initial simplex sampled randomly within a relative large area. If there were more than one local minimum located at the near territory, it would have the opportunity to wander from the same starting point, actually the starting area, to different local minima. This stochastic

mechanism provides the fundamental searching method for local minima in this proposed global optimization algorithm and a basis of being capable to explore the branches from a node.

Meanwhile, in order to prevent optimizer trapped in a local minimum surrounded by steep, several methods, such as saddle point method [10], tunneling method [11], trajectory method [10], and the Global Explorer (GE) with an escape function proposed by Isshiki [12-14], had been released.

For a practical and complicated case of optical design, the surface of merit function constructed by the parameter space is extremely intricate. In addition, the definition of merit function is not easy to describe all the views of requirements especially for the cost and manufacturing considerations. Multiple local minima are needed for a global optimization problem and they have to be re-examined for the further consideration. Thus, the GE is a very good candidate to be utilized to find multiple local minima in the merit space and even more, the exposed solutions are able to be proceeded to the further optimization with another optimization method or alternative merit function [14]. In our proposed algorithm, the concept of escape function was adopted as a framework of our non-local optimization strategy, some treatments, however, were taken to improve the efficiency in exploring within the design space.

For global explorer, the optimizer would flee from a local minimum instead of being trapped inside it due to the assistance of escape function,  $f_e$ , as following:

$$f_e = \sqrt{H} \exp\left[-\frac{1}{2W} \sum_j \mu_j (x_j - x_{j_l})^2\right], \quad (2)$$

where  $x_j$  denotes the components of the coordinate of present position lying on the  $j^{\text{th}}$  parameter,  $x_{j_l}$  is the coordinate of the current local minimum,  $\mu_j$  is the weight imposed on parameter  $x_j$ , and  $H$  and  $W$  represent the height and width of escape function, respectively.

Although the escape function can throw optimizer out of current local minimum, however, the determinations of height ( $H$ ) and width ( $W$ ) of the escape function will be an issue when the program is running. Too large values of  $H$  and  $W$  might induce an unexpected ignorance of the potential optimal solutions if several local minima cluster around the vicinity, on the contrary, too short and narrow escape function will also waste computational resources in repetitiously trying to escape by magnifying its values of height and width in case the valley is deep, wide or a steep around. Hence, the performance of GE is determined not only by the algorithm for local minimum approach but also the parameters of escape function.

For a high-dimensional parameter space, the corresponding topographic surface constructed by the merit function is difficult to be predicted and, furthermore, the height and width of the escape function are not easy to be determined in advance. A dynamic mechanism to determine the height and width of the escape function would be helpful to make the escape function to be more adaptive to the proximity of current local minimum, thus the definitions of height and width of escape function can be modified as eq. (3) and (4),

$$H = \phi(x_1^i, x_2^i, \dots, x_N^i) - \phi(x_1^m, x_2^m, \dots, x_N^m), \quad (3)$$

$$W = \sqrt{\sum_j (x_j^m - x_j^i)^2}, \quad (4)$$

where  $\phi$  is the value of merit function corresponding to the vector  $(x_1, x_2, \dots, x_n)$  in the parameter space and  $i$  and  $m$ , the superscripts of  $x_j$ , are denoted for the starting position of this trial and for the last local minimum along the  $j^{\text{th}}$  parameter axis, respectively.

Moreover, another modification in addition to the stochastic initial simplex was adopted for the downhill simplex method. The initial simplex for every trial when escaping from the current local minimum is also determined with the dependence of a “momentum” vector which is deduced from the geographic relation between the starting point and the current local minimum in the last minimization.

$$\vec{M} = (x_1^m - x_1^i, x_2^m - x_2^i, \dots, x_N^m - x_N^i). \quad (5)$$

Hence, the vertices of new initial simplex can be determined by

$$X_j = x_j^m + r \cdot l_j + w_j^M \cdot M_j, \quad (6)$$

where  $r$  is a random number between  $(-1,1)$ ,  $l_j$  is the characteristic length for sampling the initial simplex along  $j^{\text{th}}$  parameter axis, and  $w^M$  is the weight imposed on the momentum vector.

By Eq. (6) a new starting position of the optimizer will be created away from the current local minimum along a direction which is determined by the direction where it came from and the weights imposed on each vector component. The advantage of this treatment is to decrease the probability of drawing back the optimizer to the previous starting point of the last minimization.

As a short summary, randomly sampling the vertices of the initial simplex for the downhill simplex method provides it the basic ability to stochastically approach a local optimum when many of local minima entangled in a small volume with  $N$  dimensional design space. Moreover, the “momentum” vector reflects the direction where the optimizer came from and it drives the optimizer keeping going easily. Meanwhile, the dynamic determination of height and width of the escape function makes the GE be more adaptive to the topography of the valley at where the local minimum locates. A more detail exploration in the design space would be performed by the above revisions of downhill simplex method and global explorer, however, it only can be identified as a “non-local” optimizer in case the optimizer cannot roam around the entire design space. In order to supplement to this insufficiency, an additional action is necessary when the optimizer cannot find any new local minimum along the stripe.

When the tree of local minima cannot grow anymore, the optimizer has to throw a new start position somewhere in the design space. The location of new start is be determined stochastically, and it must be bounded within the design space and it also can be constrained by some rule we can pre-defined. Once the new start had been generated, a new tree structure will be established until the desired stop criteria have been satisfied. This process, we called it as “Hyper Throw”, which is the complement when the design space is divided into several “valid” portions and the optimizer has no way to pass across these walls where the value of merit function is illegal or invalid.

Figure 1 is the flow chart of our proposed global optimization scheme. All of algorithms were developed on a platform of commercial optical software, OSLO, by the Lambda Research Corp.. The algorithm is started with an initial design and will be stopped if either the desired solutions were obtained or some stopping criteria were satisfied. Every new valid solution derived from the parental local minimum by escaping minimization is called as a node. The optimizer will not magnify the parameters of the escape function unless it cannot find any new local minimum by the random simplex method under the limitation of maximum trial count. Similarly, identical rule is also suitable for tracing back to a previous existed solution when the maximum allowable trial number of magnifying escape function is exceeded. When the algorithm traced over every node of the whole tree, the procedure of hyper throw will be activated and the global optimization process will go on.

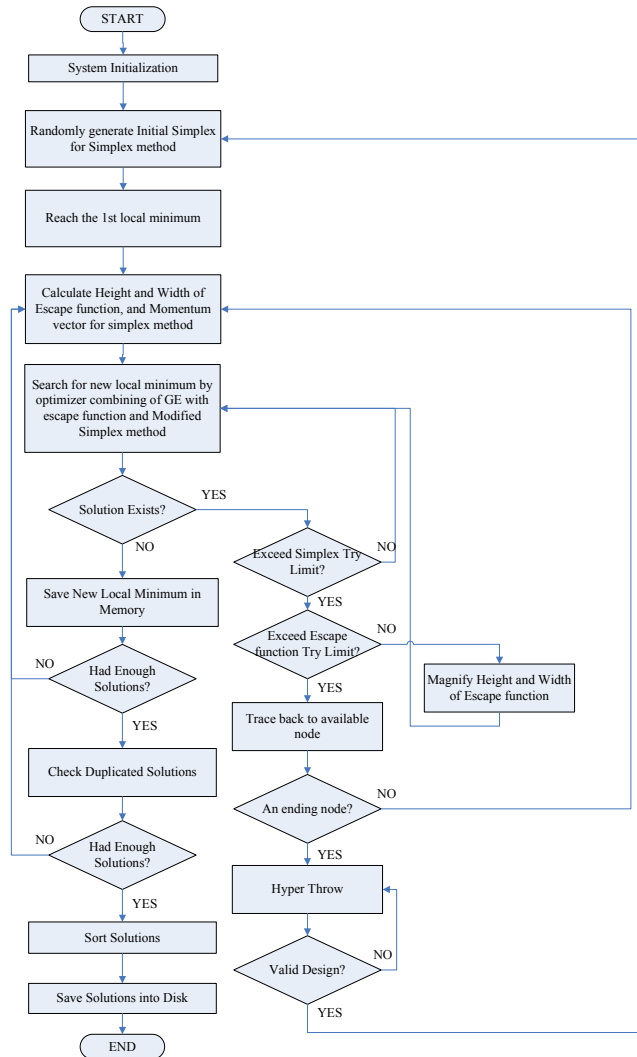


Fig. 1 Flow chart of the proposed global optimization scheme.

### 3. DESIGNS OF SINGLET ASPHERIC OBJECTIVE LENS

As a case demonstration, we considered a singlet design with two aspheric surfaces which can be described as eq.(7) to realize the compatible objective lens for CD and DVD specifications as shown in Fig. 2. The parallel incident beam will be focused by the singlet objective lens through the cover glass (protective substrate) on the image plane whatever the light wavelength is 0.78um for CD configuration or 0.65um for DVD configuration.

$$z = \frac{CVr^2}{1 + \sqrt{1 - CV^2(CC + 1)r^2}} + \sum_{n=1} AS_n r^{2n}, \quad (7)$$

where  $z$  is the surface sag,  $CV$  is the curvature of surface,  $CC$  is the conic constant and  $AS_n$ s are the aspheric coefficients corresponding to even order terms of radius  $r$ .

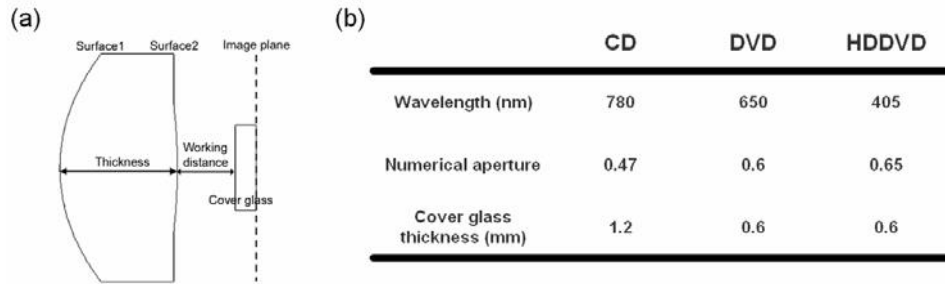


Fig. 2 (a) Schematic layout of the design of singlet objective lens. (b) The specifications of CD, DVD and HDDVD

In the preliminary stage, we only adopted 15 variables including the lens thickness, the working distances for each configuration and CV, CC, AS<sub>2</sub>, AS<sub>3</sub>, AS<sub>4</sub> and AS<sub>5</sub> of each surface to drive the merit function (objective function) to the lowest value by the proposed global optimization algorithm. For the requirement of the minimum spot size for both configurations of CD and DVD, the definition of merit function was determined as the summation of root-mean-square geometric spot size.

Figure 3 shows six designs with the lowest value of merit function which were generated by the proposed global optimization algorithm. The six solutions actually are not good enough if we analyze their point spread functions (PSF), thus a further optimization is necessary to proceed in order to obtain a better set of variables fulfilling the requirements of specifications for both CD and DVD configurations. Nevertheless, the solutions gathered by the global optimization at least are good as the new initial starts to be optimized further.

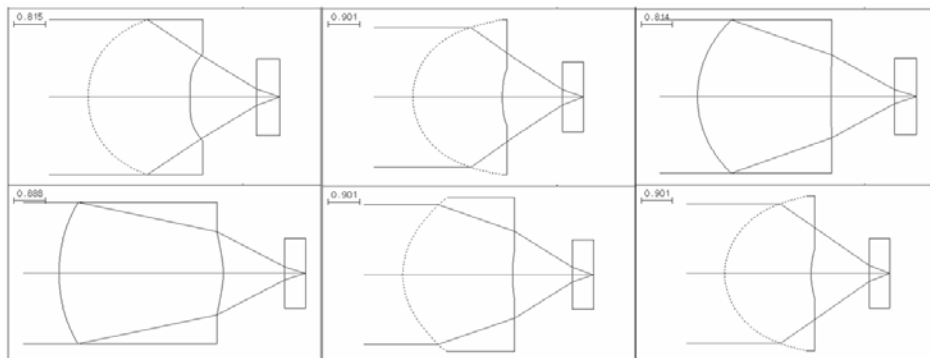


Fig. 3 The best 6 designs generated by the proposed global optimization algorithm

### 3.1 CD/DVD Compatible Objective Lens Design

The reason why we cannot obtain the best solution by the proposed scheme is that the definition of merit function did not cover all considerations except the geometric spot size. Having tiny wavefront error will directly influence the point spread function. Hence, in order to improve the optical performance and secure the required NA, new operands including the optical path difference (OPD) and the exiting angle respect to the optical axis from surface 2 are necessary to be introduced into the combination of objective functions as represented in eq. (8).

$$M = \sum_i^{\text{# of configurations}} ((w_a \times (A_i - U_i))^2 + (w_s \times S_i)^2 + (w_o \times O_i)^2), \quad (8)$$

where  $w_a$ ,  $w_s$  and  $w_o$  are the specified weights corresponding to each term.  $A_i$  represents the ray angle exited from the surface 2 respect to the optical axis,  $S_i$  is the RMS geometric spot size and  $O_i$  is the RMS wavefront error for the different configurations denoted by  $i$ .  $U_1$  and  $U_2$  are determined by the NAs required by each configuration.

Not only the merit function had been expanded but also more terms of aspheric coefficients were added. Higher terms of aspheric coefficients provided more degree of freedom to improve the performance especially for the outer area of off-axis where always makes very severe spherical aberration for ordinary spherical lens. Because it is supposed that the new starting designs obtained in the preliminary optimization are good design, it is reasonable to perform a further process only with local optimization methods. For this consideration, DLS is an efficient and effective choice to continue optimizing the designs. The further optimization process can result in a better solution of the final design which is compatible with the CD and DVD configurations. The analysis of PSF shows that the Strehl ratios are approaching to the diffraction limits for both 0.78um and 0.65um wavelengths as shown in Fig. 4 and the numerical apertures are also fulfilled with the specifications and the lens parameters listed in Table 1.

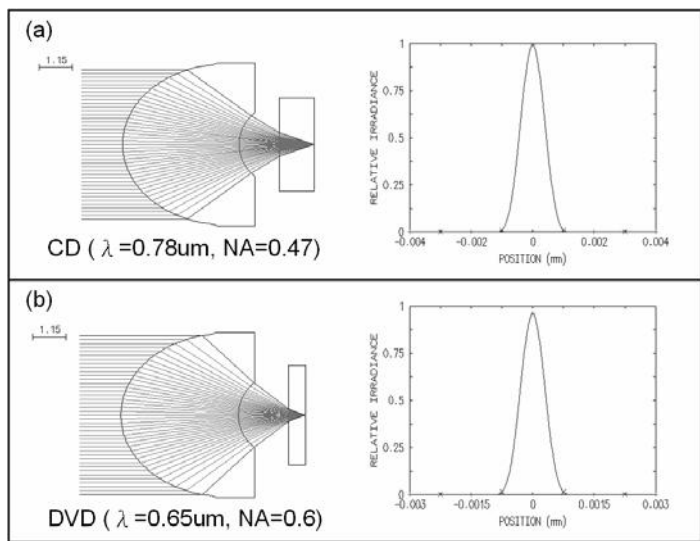


Fig. 4 The final design of a singlet objective lens compatible to CD and DVD and their PSF analysis.

Table 1 The list of lens parameters for CD/DVD compatible objective lens

Surface 1		Surface 2	
Parameter	Value	Parameter	Value
CV	0.1978	CV	0.2
CC	2.3355	CC	-9.8989e7
AS1	1.2283e-1	AS1	2.9459e-1
AS2	8.0266e-3	AS2	3.6272e-1
AS3	-1.5165e-3	AS3	-7.3460e-1
AS4	6.5984e-4	AS4	7.7210e-1
AS5	-1.5995e-4	AS5	-6.6061e-2
AS6	2.3648e-5	AS6	-3.8385e-1
AS7	-1.5370e-6	AS7	1.6260e-1
AS8	-1.4009e-8	AS8	1.4954e-2
AS9	2.5052e-9	AS9	-4.7891e-3
TH	4.0628		

### 3.2 DVD/HDDVD Compatible Objective Lens Design

The design of CD/DVD compatible objective lens can be further modified to satisfy to the specifications of DVD and HDDVD. HDDVD is one of the candidates of next generation high-density optical storage media, which uses a shorter wavelength of light source and larger NA to reduce the spot size. The 0.405 $\mu$ m wavelength of the blue-violet laser and 0.65 of numerical aperture achieve 15GB for single layer and single side. By replacing a new wavelength for the HDDVD in the configuration of CD in the CD/DVD compatible design, similar optimization process can also provide an acceptable design for DVD and HDDVD compatible singlet objective lens as shown in Fig. 5 and the corresponding lens parameters are listed in Table 2.

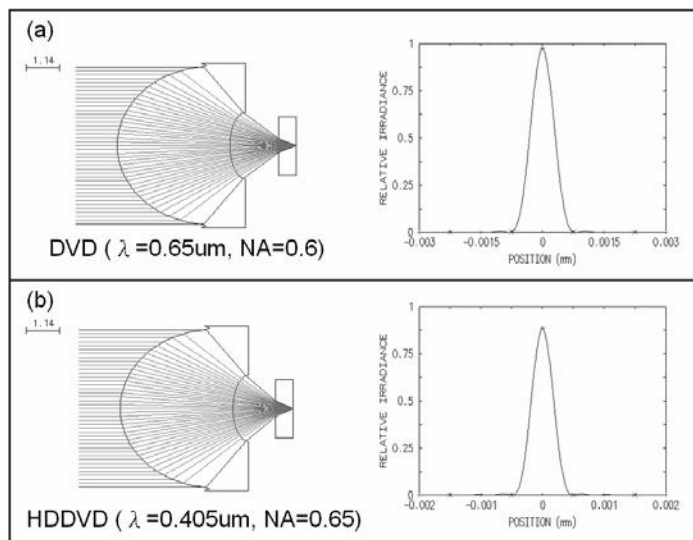


Fig. 5 The final design of a singlet objective lens compatible to DVD and HDDVD and their PSF analysis.

Table 2 The list of lens parameters for DVD/HDDVD compatible objective lens

Surface 1		Surface 2	
Parameter	Value	Parameter	Value
CV	0.4468	CV	0.1
CC	-3.0973e-1	CC	-9.8975e7
AS1	-3.1211e-3	AS1	2.0308e-1
AS2	-8.6959e-4	AS2	1.2758e-2
AS3	2.5639e-4	AS3	1.3930e-1
AS4	-2.4100e-4	AS4	-9.3529e-3
AS5	1.3824e-4	AS5	-6.6156e-1
AS6	-3.4090e-5	AS6	1.0076
AS7	-3.6306e-7	AS7	9.2529e-1
AS8	1.5601e-6	AS8	-3.4738
AS9	-1.0084e-7	AS9	2.4938
AS10	-1.054e-8	AS10	6.2227e-1
AS11	9.3385e-9	AS11	-1.4319
AS12	-4.7618e-10	AS12	4.5883e-1
TH	3.8625		



## 4. CONCLUSIONS

Owing to the extreme high requirement of performance, very small spot size and RMS wavefront error, pure geometric spot size as the only component of the merit function might be not enough to drive the global optimization algorithm to the best solution directly. However, the proposed optimization scheme still can be utilized as a very powerful initial design generator to provide much suitable initial positions as the new start locations to the better designs as we demonstrated in this paper. Two designs of singlet aspheric objective lens which are compatible to CD/DVD and DVD/HDDVD were obtained by this method. Therefore, having a single design for more than two configurations is worth to expect but indeed, the chromatic dispersion, different numerical apertures and the disparate thicknesses of the protective substrate for different specifications, such as CD, DVD, HDDVD and Blu-ray, magnificently raise the difficulty of finding a perfect set of lens parameters even the higher order aspheric polynomial was utilized to describe the surfaces of single lens.

**Acknowledgements:** This work is partially supported by the National Science Council, ROC, under contract no. NSC 93-2215-E009-057. This work is also partially supported by the MOE ATU program at the National Chiao Tung University. We thank the Lambda Research Corp. for the educational support of software, OSLO.

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