Optimization of adaptive nonlinear aspherical microlens using ZEMAX

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ABSTRACT

This paper presents a comprehensive analysis of a thin plate of nonlinear medium (TPNM) irradiated by a laser Gaussian beam (LGB), which functions as a tunable nonlinear aspherical micro lens (NAML). When positioned at the beam waist of the LGB, the TPNM behaves as a Kerr-based lens with variable curvature and conic coefficient. Analytical expressions for the vertex curvature radius and conic coefficient are derived based on design parameters such as beam waist radius, peak intensity, nonlinear coefficient of refractive index, and physical thickness of TPNM. To verify and optimize lens performance, the optical design software ZEMAX is employed to extract and evaluate optical aberration, spot diagrams, and wavefront error. The optimization significantly reduces aberrations, spot size, and wavefront error, thereby enhancing imaging quality. The results confirm the feasibility of using NAMLs in complex optical systems requiring adaptive aberration control, making them suitable for integration into compact, high-resolution optical platforms.

Keywords: Nonlinear optics; Aspherical micro lens; Conic coefficient; ZEMAX Software; Aberration optimization.

1. INTRODUCTION

The design and correction of the optical aberrations remain central challenges in developing high-precision imaging systems, especially at the micro-scale [1, 2]. Aspherical lenses have long been used to mitigate third-order aberrations such as spherical aberration and coma; however, traditional manufacturing techniques impose fixed geometric parameters, limiting their adaptability in dynamic or tunable environments [3].

Recent advances in nonlinear optics have enabled new approaches to adaptive lens design. Specifically, nonlinear Kerr media offer a unique advantage: their refractive index can be modulated by the intensity of an incident optical field [4, 5]. This property opens the possibility of realizing a NAML, in which the curvature and conic coefficient of the lens surface are not fixed but instead vary with controllable beam parameters such as power and waist radius.

Although the theoretical feasibility of NAML has been demonstrated in prior works [6, 7], these studies primarily focused on analytical derivations of lens parameters and wavefront modeling. However, limited attention has been given to evaluating the optical performance of NAMLs within optical design environments or incorporating them into simulation-based system models. To address this gap, the present study conducts analytical modeling and optimization of the NAML using ZEMAX software, aiming to quantify aberration behavior and enhance lens performance through simulation-guided design.

The primary objective is to determine how laser beam parameters influence third-order aberrations and image quality, and to apply optical optimization techniques to minimize aberrations such as spherical aberration and coma [2, 8, 9]. The analysis begins with analytical derivations of curvature radius and conic coefficient under Kerr-induced index modulation, followed by ZEMAX-based simulation and merit-function optimization. This approach not only validates the theoretical model but also provides a simulation framework for exploring the integration of NAMLs into dynamically adjustable optical systems with tunable aberration correction. In particular, this study targets the application of NAMLs in miniature adaptive imaging modules, such as fiber-optic endoscopic systems or MEMS-based optical units, where compactness and active aberration control are critical.

2. MODEL OF THE NONLINEAR ASPHERICAL MICRO LENS

The physical model considered in this study is based on a thin planar layer of a nonlinear optical medium with a Kerr-type response. When a continuous-wave Gaussian beam is tightly focused at the center of the nonlinear layer, the intensity distribution across the transverse plane induces a radial variation in refractive index due to the optical Kerr effect. This phenomenon effectively transforms the thin film into a lens-like structure exhibiting aspherical characteristics.

Let the nonlinear medium possess a linear refractive index n_0, a nonlinear index coefficient n_2, and physical thickness d_{phys}. The incident laser beam has a waist radius W_0 and peak intensity I_0. For a fundamental TEM_{00} mode, the beam intensity profile is described by [1, 4]:

$$I(\rho)=I_0\exp\left(-\frac{2\rho^2}{W_0^2}\right) \tag{1}$$

The refractive index distribution becomes [1, 4]:

$$n(\rho)=n_0+n_2I(\rho)=n_0+n_2I_0\exp\left(-\frac{2\rho^2}{W_0^2}\right) \tag{2}$$

Near the optical axis ($\rho \ll W_0$), the exponential term can be expanded using a Maclaurin series, truncated to the fourth order:

$$n(\rho)=n_0+n_2I_0\left(1-\frac{2\rho^2}{W_0^2}+\frac{2\rho^4}{W_0^4}\right) \tag{3}$$

This refractive index gradient causes a spatial variation in optical path length, which can be interpreted as an equivalent deformation of the wavefront - referred to as the optical sag $z(\rho)$. Under the thin lens approximation, this induced sag is modeled as:

$$z(\rho)=\Delta n(\rho).d_{phys}=\frac{2n_2I_0d_{phys}\rho^2}{W_0^2}-\frac{2n_2I_0d_{phys}\rho^4}{W_0^4}=A\rho^2+B\rho^4 \tag{4}$$

The use of a Maclaurin series expansion to approximate the Gaussian intensity distribution has been presented in various previous works. However, the expansion to the fourth-order form in Eq. (3), and its subsequent transformation into the simplified sag function in Eq. (4), constitute a new contribution of this study.

Here, the coefficient $A=\frac{2n_2I_0d_{phys}}{W_0^2}$ corresponds to the curvature of the spherical surface at the vertex, while $B=-\frac{2n_2I_0d_{phys}}{W_0^4}$ characterizes the degree of aspherical.

To establish correspondence with a conventional aspherical lens, we compare this form to the classical sag equation [1, 2]:

$$z(\rho)=\frac{\rho^2}{R\left(1+\sqrt{1-(1+k)\rho^2/R^2}\right)} \tag{5}$$

where R is the curvature radius at the vertex, and k is the conic constant, which determines the particular shape of the optical surface. Using the Taylor expansion with the condition $\rho / R \to 0$, which is analogous to the near-axis condition $0 < \rho << W_0$, equation (5) will be:

$$z(\rho) = \frac{\rho^2}{R\left(1+\sqrt{1-(1+k)\rho^2/R^2}\right)} = \frac{\rho^2}{2R} + \frac{\rho^4}{8R^3}(k+1) \tag{6}$$

Comparing Eq. (4) to Eq. (6), we have:

$$\begin{cases} R = \dfrac{W_0^2}{4n_2 I_0 d_{phys}} \\ k = -1 - \dfrac{W_0^2}{4(n_2 I_0 d_{phys})^2} \end{cases} \tag{7}$$

These parameters allow us to define an equivalent aspherical lens that mimics the optical behavior of the nonlinear medium under a specific laser intensity distribution. Importantly, this equivalence enables a powerful modeling strategy: the nonlinear lens can be represented within optical design software, such as ZEMAX, as an aspherical element characterized by the extracted *R* and *k* values.

This equivalence yields two significant implications for optical modeling and system integration:

Validation through simulation: The equivalent aspherical lens can be directly embedded into sequential or non-sequential optical systems in ZEMAX. This enables comprehensive performance analysis through ray tracing, including spot diagram generation, wavefront error evaluation, and Zernike polynomial decomposition.

Optimization of nonlinear systems: By adjusting the input laser parameters, such as power and beam waist, one can indirectly modulate the curvature radius *R* and conic constant *k*, thereby controlling the aberration characteristics of the system. ZEMAX's merit function framework can then be employed to iteratively optimize these parameters for enhanced imaging quality.

Consequently, this modeling approach provides both a physical understanding and a practical toolchain for designing adaptive, power-tunable aspherical micro lenses. It bridges nonlinear optics with classical optical design, enabling real-world deployment of nonlinear media in compact and dynamically adjustable imaging systems.

3. ZEMAX-BASED SIMULATION AND OPTIMIZATION OF THE NONLINEAR ASPHERICAL MICROLENS

To validate the theoretical model and explore the practical implementation of the NAML, we performed a numerical simulation and optimization process using the ZEMAX optical design software. The objective was to quantify the third-order aberrations of the nonlinear lens, evaluate imaging performance, and determine optimal beam-material configurations that yield minimal aberration [1, 2].

The process begins by calculating the initial values of the curvature radius R and conic coefficient k based on the Gaussian beam and nonlinear medium parameters [6, 8]. Given a peak intensity $I_0 = 10^4\ W/cm^2$, beam waist radius $W_0 = 10^{-2} cm^2$, nonlinear coefficient $n_2 = 10^{-6} cm^2/W$, and film thickness $d_{phys} = 0.06\ cm$.

Based on the specified system parameters and using Eq. (7), the vertex curvature radius and conic coefficient of the equivalent aspherical surface are determined as follows:

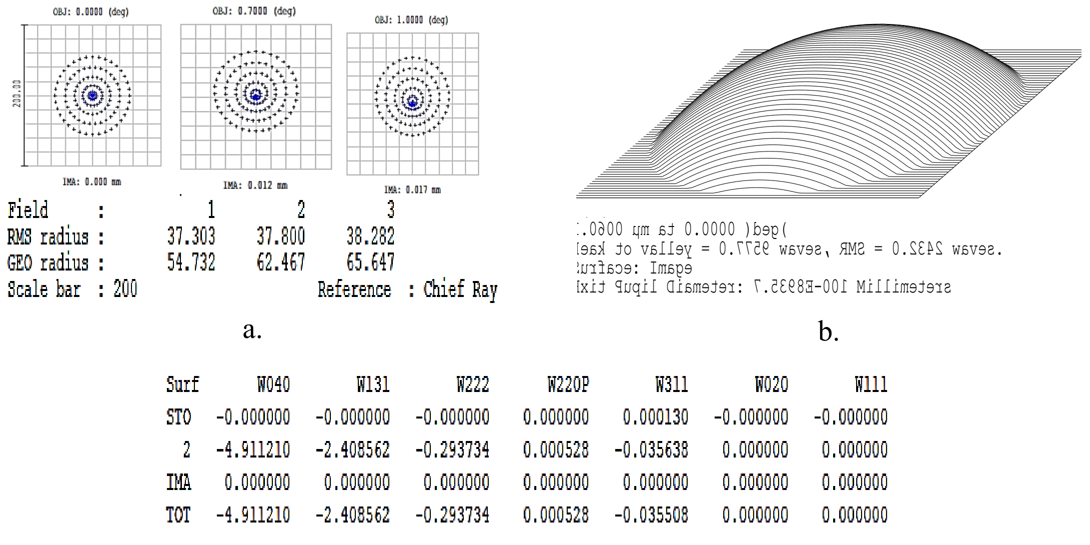
$$\begin{cases} R = 0.417\ mm \\ k = -70.444 \end{cases} \tag{8}$$

These parameters define an equivalent aspherical surface that is geometrically identical to the output wavefront produced by the nonlinear layer under the specified excitation conditions. This surface was implemented in ZEMAX as a custom asphere using the calculated values of curvature radius *R* and conic coefficients *k*, with the full configuration - including surface types, radius, thicknesses, materials, and conic coefficients, summarized in table 1. Symbol "V" is Variable and symbol "M" is Marginal Ray High, set at a ray height of 0.

Table 1. *Parameters of the origin equivalent aspherical in ZEMAX software.*

Surf: Type		**Radius (mm)**		**Thickness (mm)**		**Glass**	**Semi-Diameter (mm)**	**Conic**	
OBJ	Standard	Infinity		Infinity			Infinity	0.000	
STO	Standard	Infinity		1.000	V	1.45,64.2	0.1	0.000	
2	Standard	-0.417	V	0.944	M		0.112	-70.444	V
IMA	Standard	Infinity		-			0.082	0.000	

Using this initial configuration, a ray-tracing simulation was carried out in ZEMAX to evaluate the optical performance of the system. Key metrics were analyzed, including spot diagrams, wavefront error, and third-order Seidel aberrations [2, 9]. The root-mean-square (RMS) spot radius at the image plane was approximately 38 μm, while the geometric (GEO) spot radius reached 65 μm (figure 1a), indicating pronounced beam spreading. The wavefront error map (figure 1b) showed a peak-to-valley deviation of 0.7759λ and an RMS value of 0.2342λ, reflecting significant deviation from the ideal wavefront. Third-order aberrations were also observed, with spherical aberration $W_{040} \approx -4.9\lambda$ and coma $W_{131} \approx -2.4\lambda$ (figure 1c), confirming the system's degraded imaging performance.



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Field      :         1        2        3
RMS radius :    37.303   37.800   38.282
GEO radius :    54.732   62.467   65.647
Scale bar  : 200                Reference  : Chief Ray
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a.

b.

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Surf      W040        W131        W222       W220P        W311        W020        W111
STO  -0.000000   -0.000000   -0.000000    0.000000    0.000130   -0.000000   -0.000000
  2  -4.911210   -2.408562   -0.293734    0.000528   -0.035638    0.000000    0.000000
IMA   0.000000    0.000000    0.000000    0.000000    0.000000    0.000000    0.000000
TOT  -4.911210   -2.408562   -0.293734    0.000528   -0.035508    0.000000    0.000000
```

c.

Figure 1. *Image quality rating chart of the origin equivalent aspherical:*
a. Spot diagram; b. Wavefront error map; c. Seidel aberration coefficient in waves.

To enhance the quality of the NAML system, we employed the "Sequential Merit Function Editor" within ZEMAX to perform a structured optimization. The merit function was constructed to minimize the root-mean-square (RMS) spot radius, suppress third-order aberrations, and improve wavefront error.

The optimization variables were selected as the vertex curvature radius (R), the conic constant (k), and the lens thickness (d). These parameters were chosen due to their direct influence on the wavefront shape and aberration characteristics. To ensure physical feasibility and manufacturability, constraints were introduced. These included bounds on the curvature radius and conic coefficient to avoid unrealistic surface geometries, and limits on thickness to maintain compatibility with the selected nonlinear medium. The range of allowed parameter variation was determined based on the material refractive index profile and nonlinear deformation limits under laser excitation.

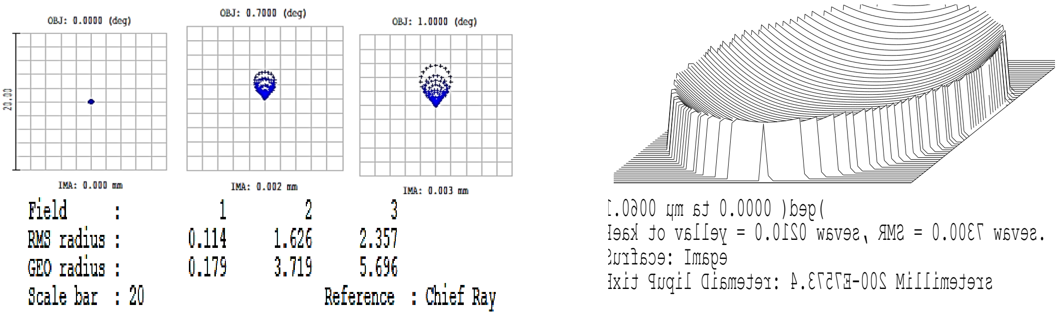
During the optimization process, we iteratively adjusted the selected variables to minimize the total merit function, which combined the weighted contributions of spot size, wavefront error. After several cycles, the system converged to an optimized configuration that significantly improved imaging resolution while respecting the physical constraints of the system, as shown in table 2.

To minimize experimental noise, we assume a stable Gaussian beam profile in simulations. In practice, intensity fluctuations can be reduced using stabilized laser sources, ensuring accurate extraction of lens parameters like curvature and conic coefficient.

Table 2. *Parameters of the equivalent aspherical after optimization.*

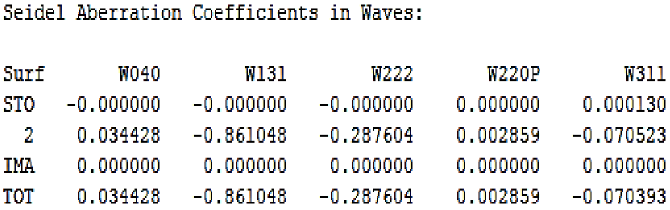
Surf: Type		Radius		Thickness		Glass	Semi-Diameter	Conic	
OBJ	Standard	Infinity		Infinity			Infinity	0.000	
STO	Standard	Infinity		1.400	V	1.45,64.2	0.1	0.000	
2	Standard	-0.077	V	0.174	M		0.116	-2.076	V
IMA	Standard	Infinity		-			8.868E-003	0.000	

After optimization, the optical performance of the nonlinear lens was significantly enhanced. The RMS spot radius at the maximum field point was reduced to 2.36 µm, while the geometric (GEO) spot radius decreased to 5.70 µm (figure 2a). The wavefront error map (figure 2b) exhibited a peak-to-valley deviation of 0.0120λ and an RMS value of 0.0037λ, indicating near-diffraction-limited performance. Third-order aberrations were also markedly suppressed, with the spherical aberration W_{040} reduced to 0.034λ and the coma W_{131} lowered to -0.861λ (figure 2c).



```
Field      :        1        2        3
RMS radius :    0.114    1.626    2.357
GEO radius :    0.179    3.719    5.696
Scale bar  : 20             Reference  : Chief Ray
```

a. b.



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Seidel Aberration Coefficients in Waves:

Surf        W040        W131        W222       W220P        W311
STO    -0.000000   -0.000000   -0.000000    0.000000    0.000130
  2     0.034428   -0.861048   -0.287604    0.002859   -0.070523
IMA     0.000000    0.000000    0.000000    0.000000    0.000000
TOT     0.034428   -0.861048   -0.287604    0.002859   -0.070393
```

c.

Figure 2. *Image quality rating chart of the equivalent aspherical after optimization: a. Spot diagram; b. Wavefront error map; c. Seidel coefficient.*

At this point, the equivalent lens geometry defined by the optimized values of *R'* and *k'* can be reverse-engineered to determine the physical parameters of a nonlinear lens that would produce such a profile under Kerr-induced deformation. From the known curvature, conic coefficient and $d'_{phys} = 1.4$, we have:

$$\begin{cases} R' = \dfrac{W_0^2}{4n_2 I_0 d} = 0.077 \\ d'_{phys} = 1.4 \\ k' = -1 - \dfrac{W_0^2}{4(n_2 I_0 d)^2} = -2.076 \end{cases} \tag{9}$$

Based on the reverse-engineered optical parameters obtained from the ZEMAX optimization, the corresponding configuration of the nonlinear lens is determined as follows: a dry thin film of Oil Red O is used as the nonlinear medium, characterized by a linear refractive index $n_0 = 1.45$, a nonlinear refractive index coefficient $n_2 = 10^{-6} cm^2 / W$, and a physical thickness $d_{phys} = 0.14\ cm$. The excitation source is a conventional Neodymium laser operating at a wavelength $\lambda = 1.06\ \mu m$, focused to produce a Gaussian beam with a waist radius $W_0 = 1.48 \times 10^{-2} cm$. The resulting beam delivers a peak intensity of $I_0 = 5.11 \times 10^4\ W / cm^2$, so the average power of $P_{ave} = 17.69\ W$ which corresponds to the optimized lens geometry derived in simulation.

This integrated approach from analytical modeling to numerical simulation, optimization, and inverse mapping demonstrates a powerful framework for engineering nonlinear adaptive lenses. By leveraging ZEMAX as both a verification and optimization tool, the NAML can be rigorously designed and integrated into compact, high-performance optical systems requiring real-time aberration control.

4. CONCLUSIONS

In this study, we proposed and developed a method for designing a NAML based on a thin Kerr-type nonlinear medium irradiated by a Gaussian laser beam. By establishing analytical expressions that relate the geometric characteristics of the lens, namely, the curvature radius and conic coefficient, to physical parameters such as peak intensity, beam waist radius, nonlinear refractive index, and material thickness, we formulated an equivalent aspherical surface representation. This equivalence enabled direct integration of the NAML into the ZEMAX optical design software for performance evaluation and optimization. The simulation results demonstrated the ability to effectively control third-order aberrations, reduce spot size, and significantly reduce wavefront error.

Furthermore, a reverse-engineering procedure was successfully employed to retrieve the corresponding laser and material parameters that produce the optimized lens geometry. This closed-loop workflow from theoretical modeling to practical implementation establishes a robust framework for designing power-tunable micro-optical elements using standard simulation tools and nonlinear optical materials. Unlike conventional static aspherical lens design, which depends on fixed geometries and complex fabrication, the proposed NAML approach enables tunable aberration correction by adjusting laser parameters. This flexibility makes it suitable for integration into compact, high-resolution optical systems where dynamic adaptation is required.

From a practical perspective, several challenges and future directions should be noted. High-power laser excitation may impose thermal and mechanical limitations on the nonlinear medium, potentially affecting its long-term performance. Therefore, in future experimental optimization, appropriate parameter selections should be made to ensure technological feasibility and material longevity. In addition, future work could investigate the use of nonlinear materials with negative nonlinear coefficients ($n_2 < 0$) and explore the integration of NAMLs into multi-element optical systems to broaden the scope of aberration correction and functionality. This work lays the groundwork for future integration of NAML into micro-lens systems or nonlinear imaging architectures.

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TÓM TẮT

Tối ưu vi thấu kính phi cầu phi tuyến thích nghi bằng phần mềm ZEMAX

Bài báo này trình bày một phân tích toàn diện về một lớp mỏng vật liệu phi tuyến (TPNM) được chiếu bởi chùm laser Gaussian (LGB), hoạt động như một thấu kính vi mô phi cầu phi tuyến có thể điều chỉnh (NAML). Khi được đặt tại mặt thắt chùm tia của LGB, lớp TPNM thể hiện đặc tính của một thấu kính Kerr với bán kính cong và hệ số conic có thể thay đổi. Các biểu thức giải tích cho bán kính cong tại đỉnh và hệ số conic được xây dựng dựa trên các tham số thiết kế như bán kính mặt thắt chùm tia, cường độ đỉnh, hệ số chiết suất phi tuyến và chiều dày vật lý của TPNM. Để kiểm tra và tối ưu chất lượng thấu kính, phần mềm thiết kế quang học ZEMAX được sử dụng để trích xuất và đánh giá quang sai, biểu đồ vết ảnh và sai sóng. Quá trình tối ưu hóa giúp giảm đáng kể quang sai, kích thước điểm ảnh và sai sóng, từ đó nâng cao chất lượng ảnh. Kết quả xác nhận tính khả thi của việc sử dụng NAML trong các hệ thống quang học phức tạp yêu cầu điều chỉnh quang sai thích nghi, phù hợp để tích hợp vào các hệ thống quang học nhỏ gọn, độ phân giải cao.

Từ khoá: Quang phi tuyến; Vi thấu kính phi cầu; Hệ số conic; Phần mềm ZEMAX; Tối ưu quang sai.