

Coupling Efficiency Optimization for the Optical Fiber Lens with Oval-Shaped Endfaces by Applying Uniform Design and Kriging Interpolation

Chialing Hsieh, Fangchen Dong, and Chengkang Lee

Abstract—The purpose of this study is to optimize the coupling efficiency of an optical fiber lens by applying the uniform design of experiments and Kriging interpolation methods. A third-generation optical fiber endface polishing machine is applied to polish the optical fiber endfaces into oval shapes. A type-36 optical fiber fusion splicer is used to fuse the optical fibers into a lens. In the polishing process, the control factors are polishing angle, feeding rate, and rotation speed. Firstly, the uniform design of experiments method is used to construct a set of experiments. The constructed experiments are scattered uniformly in the design space formed by the control factors. Secondly, the coupling efficiency of the lens in each experiment is measured using a 980 nm laser diode and a power meter. Thirdly, the Kriging interpolation method is used to transform the discrete data of coupling efficiency into a continuous surrogate model of coupling efficiency. Finally, a mixed optimization algorithm combining a global search algorithm, genetic algorithm (GA), and a local search algorithm, Nelder-Mead simplex (NMS) algorithm, is used to optimize the coupling efficiency. The optimal solutions of polishing angle, feeding rate, and rotation speed are 56°, 289 rpm, and 52 $\mu\text{m}/\text{rev}$, respectively. By integrating the uniform design of experiments method and Kriging interpolation method, the coupling efficiency of the optical fiber lens can be improved from 60.89% to 79.63%. The improved rate of the coupling efficiency is 30.8%.

Index Terms—Fiber lens coupling efficiency, Kriging interpolation, laser diode, uniform design.

I. INTRODUCTION

The rise of the internet has driven demand for high-speed data transmission. Because of this demand, conventional twisted-pair transmission has been replaced by optical fiber transmissions, which exhibit an ultrahigh frequency, high capacity, low transmission loss, and immunity to electromagnetic interference. Therefore, such communications have become necessary and irreplaceable. However, problems associated with optical power loss have occurred due to an increase in transmission distances. The optical fiber communication process involves an optical

transmitter coupling a laser beam into an optical fiber for an optical signal's long-distance and low-loss transmission through an optical fiber, followed by an optical receiver that converts the optical signal into an electrical signal.

The internal structure of an optical fiber comprises three elements: core, cladding, and jacket. The core is the central part of an optical fiber, the cladding is the layer that covers the core, and the jacket is the outer layer of an optical fiber. Classified by the transmission mode, optical fibers are generally divided into single-mode fibers and multimode fibers. Multimode fibers can be used for multiple transmission modes, but mutual interference might occur because of the various transmission paths and speed of different transmission modes, thus reducing the quality of signal transmission. Accordingly, multimode fibers are more suitable for short-distance transmissions. By contrast, single-mode fibers can only be used for a single transmission mode. They exhibit an extremely low transmission loss rate and are appropriate for high-capacity and long-distance transmissions.

Numerous factors influence the transmission efficiency of optical fiber communication systems. In particular, the coupling efficiency between lasers and optical fibers directly influences the initial transmission power. Before discussing coupling efficiency, the optical modes of lasers and single-mode fibers should be compared. An optical mode comprises a mode field and a wave-front; lasers have oval mode fields and cylindrical wave-fronts, whereas single-mode fibers have spherical mode fields and plane wave-fronts. If the mode fields of a laser beam and a single-mode fiber mismatch, their coupling efficiency decreases 20% to 30% [1]. Conversely, the optimal coupling efficiency is achieved when their mode fields match completely. Several approaches have been developed to match two mode fields: changing the optical mode of a laser beam from its emitting surface to match the optical mode of a single-mode optical fiber [2], [3]; installing a lens between their two optical modes, which enables a laser beam to change its mode fields to match that of a single-mode fiber [4], [5]; and fabricating various fiber microlenses on the endface of a single-mode fiber, which are then directly coupled with laser beams [6]–[11]. Among these approaches, the use of fiber microlenses is the easiest, the most effective, and the cheapest. Various methods are used to fabricate fiber microlenses, including production processes involving photolithographic, fusion-stretching, hydrofluoric-acid-etching, carbon-dioxide-laser-processing,

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Chialing Hsieh and Chengkang Lee are with the Department of Industrial Engineering and Management, Cheng Shiu University, Kaohsiung, Taiwan (e-mail: k6758@gcloud.csu.edu.tw, cklee@gcloud.csu.edu.tw).

Fangchen Dong is with the College of Mechanical and Electrical Engineering, Shandong Yingcai University, Jinan, Shandong, China (e-mail: 28891181@qq.com).

and mechanical polishing techniques [12]-[14]. Production processes that use photolithographic, fusion-stretching, and hydrofluoric-acid-etching techniques are appropriate for axially symmetric fiber microlenses for lasers with a spherical mode. Moreover, laser-processing or mechanical polishing techniques are required to fabricate an asymmetrically curved structure on an optical fiber endface. Laser-processing techniques entail the use of an expensive laser-sintering machine, and thus are not cost-effective. Conversely, mechanical polishing techniques facilitate an easy production process of fiber microlenses that match 980-nm-high laser mode fields. Because the production of asymmetric fiber microlenses requires multiple polishing processes and exhibits low repetitiveness, the yield rate is low. To increase the yield rate and repetitiveness of the production process, a single-step method is required. In 2006, Liu and Tsai [15] developed the first polishing machine for asymmetric fiber endfaces. This machine involves periodical changes of the normal pressure between its polishing wheel and fiber endfaces, improvement in the material removal rate, and a single-step polishing process for oval-cone-shaped optical fiber endfaces. In 2007, Lin *et al.* [16] proposed a method for producing axially asymmetric oval-cone-shaped fiber lenses by using electric arc to fuse asymmetric oval-cone-shaped optical fiber endfaces. In the same year, Tsao and Tsai [17] developed the second generation of the optical fiber endface polishing machine using a torque control mechanism; the machine facilitates torque control of a direct current brush motor, pressure control of the motor, and production of variously shaped optical fiber endfaces by using voltages with different waveforms. In 2008, Hsieh and Tsai [18] introduced the third-generation polishing machine, which is based on a bivariate curvature. The machine produces optical fibers that have a bivariate-curvature-shaped longitudinal and cross-sectional surface. This machine simultaneously and periodically changes the relative position between optical fibers and the polishing wheel to control the material removal rate on the random points on a fiber endface and facilitates a single-step polishing process for the fabrication of required endfaces. The endfaces produced using this machine are similar to bivariate-curvature-shaped optical fiber endfaces. In 2010, Chen, Huang, and Tsai [19] improved the third-generation machine and its process parameters and used experimental parameters and equation derivation to obtain equations for calculating material removal rates in optical fiber polishing processes.

This study uses the third-generation optical fiber endface polishing machine to polish optical fibers exhibiting various endface shapes before using a fusion splicer to fuse the polished optical fibers into optical fiber lenses. Subsequently, the coupling efficiency of these optical fiber lenses is measured using a 980-nm laser diode and a power meter. The measurement results are then used to evaluate the quality of the optical fiber lenses. Finally, a scanning electron microscope (SEM) is employed to observe the surfaces of the lenses. To maximize the coupling efficiency, this study incorporates three process parameters, polishing angles, feed

rates, and rotation speed, in the control factors. The uniform design table $U_{15}^{*}(15^7)$ is used for planning the experimental points, and the coupling efficiency of each experimental point is measured. The values of control factors and the results of coupling efficiency of the experiments are subsequently used to establish the Kriging surrogate model of coupling efficiency. Moreover, a mixed algorithm combining a global search algorithm, genetic algorithm (GA), and a local search algorithm, Nelder-Mead simplex (NMS) algorithm, is used to maximize the Kriging surrogate model of coupling efficiency. Therefore, the optimal design values of control factors and the maximum value of coupling efficiency are obtained. Finally, the maximum value of coupling efficiency is compared with the original value of coupling efficiency to verify the applicability of the optimal design values of control factors.

II. EXPERIMENTAL EQUIPMENT

The experimental equipment used in this study comprises a third-generation optical fiber endface polishing machine, a type-36 optical fiber fusion splicer, and a measurement module for coupling efficiency. The third-generation optical fiber endface polishing machine is as shown in Fig. 1. The machine polishes thin and bare optical fiber endfaces into various geometric shapes using mechanical polishing. As shown in Fig. 2, the type-36 optical fiber fusion splicer fabricates the optical fiber lenses in endfaces using electric arc discharge. The measurement module used to measure the coupling efficiency of the polished optical fiber lenses is as shown in Fig. 3. The module is equipped with a 980-nm laser diode, an optical power meter, a tri-axial motion platform, and thermoelectric coolers.

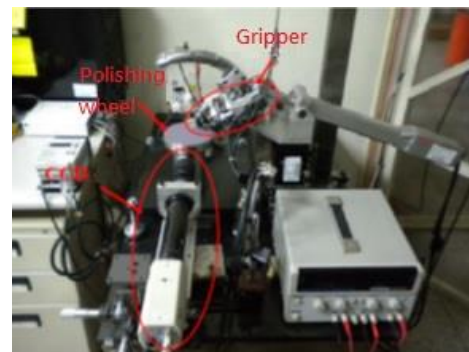


Fig. 1. The third-generation optical fiber endface polishing machine.



Fig. 2. The type-36 optical fiber fusion splicer.

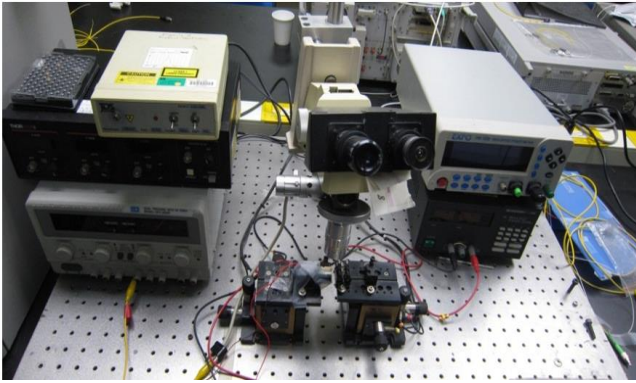


Fig. 3. The measurement module for the coupling efficiency of optical fiber lenses.

III. DESIGN OF EXPERIMENTS

As shown in Table I, three control factors A, B, and C are selected in the polishing process. The meanings of A, B, and C are polishing angle, rotation speed, and feed rate, respectively. The original design values of A, B, and C are 46° , 340 rpm, and $53 \mu\text{m/rev}$, respectively. At this original design point, the original value of coupling efficiency is only 60.89%. Therefore, it is necessary to improve the coupling efficiency by improving the values of factors.

TABLE I: LOWER AND UPPER LIMITS OF THE CONTROL FACTORS

Factor	Meaning	Unit	Lower limit	Upper limit
A	Polishing angle	$^\circ$	32	60
B	Rotation speed	rpm	280	400
C	Feed rate	$\mu\text{m/rev}$	48	58

The uniform design of experiments method, briefly denoted by UD method, is used to plan a set of experiments in this study. The UD method was proposed by Fang [20] and Wang and Fang [21]. The UD method can be used to construct a set of experimental points scattered uniformly on the continuous design space formed by the control factors. In other words, the UD method is a kind of space filling design method. Compared with the orthogonal design (OD) method, which considers the symmetrical comparability of experimental points, the UD method considers the uniform distribution of experimental points. With the UD method, a significant amount of information can be obtained for exploring the relationships between the response and the contributing factors within a small number of experimental runs. Moreover, the UD method is robust to the underlying model assumption, which means the UD method performs well even if the form of the regression model is not known [22]. Therefore, the UD method is very suitable for the problems with multiple parameters and multiple levels [23].

There are four steps to construct the experiments when applying the UD method. The first step is to determine the number of experiments. The second step is to select an appropriate uniform table that can accommodate all factors and all experiments. The third step is to determine the columns to be used according to the use table of the selected uniform table in the second step. The fourth step is to replace the number of levels of factors in the uniform table by the real values of levels of factors. Because the resource of time is

limited, the number of experiments is also limited. By considering the limited resource of time, the number of experiments is set to 15 in this study. After determining the number of experiments, the next step is to choose an appropriate uniform table that can accommodate 3 factors and 15 experiments. According to the uniform design of experiments method, the uniform table $U_{15}^*(15^7)$ is chosen to create the experimental table. By inquiring the use table of $U_{15}^*(15^7)$, columns 1, 2, and 6 should be selected. By combining the uniform table $U_{15}^*(15^7)$ and the use table of $U_{15}^*(15^7)$, the experimental table that has 3 factors and 15 experiments can be created as shown in Table II.

TABLE II: THE EXPERIMENTAL TABLE

Exp. No.	A	B	C
1	32	280	58
2	34	380	55
3	36	480	52
4	38	260	49
5	40	360	46
6	42	460	59
7	44	240	56
8	46	340	53
9	48	440	50
10	50	220	47
11	52	320	60
12	54	420	57
13	56	200	54
14	58	300	51
15	60	400	48

IV. RESULTS OF EXPERIMENTS

There are three steps to measure the results of the 15 experiments. The first step is to polish the optical fiber endfaces into oval shapes by using the third-generation optical fiber endface polishing machine as shown in Fig. 1. The second step is to fuse the optical fibers into lenses by using the type-36 optical fiber fusion splicer as shown in Fig. 2. The third step is to measure the coupling efficiencies of the lenses by using the measurement module as shown in Fig. 3. Here, an SEM is also applied to observe the endfaces of the polished fibers. The coupling efficiencies of the optical fiber lenses in the 15 experiments are obtained as shown in Table III.

TABLE III: THE COUPLING EFFICIENCIES OF THE 15 EXPERIMENTS

Exp. No.	Coupling efficiency (%)
1	32.89
2	36.09
3	41.91
4	43.17
5	38.43
6	41.37
7	49.53
8	60.89
9	57.58
10	67.33
11	66.14
12	70.88
13	75.63
14	78.61
15	65.96

The 14th experiment has the highest coupling efficiency 78.61%, in which the corresponding settings of A, B, and C are 58 °, 300 rpm, and 51 $\mu\text{m}/\text{rev}$, respectively. By using the SEM, the side and top views of the endface of the polished fiber at the 14th experiment is as shown in Fig. 4.

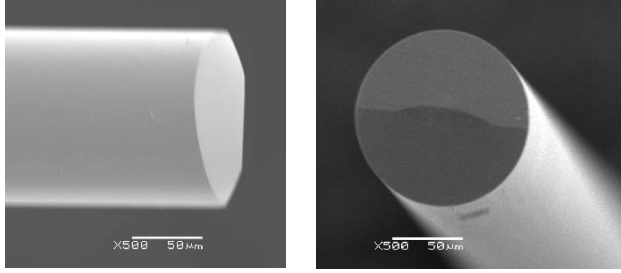


Fig. 4. The side and top views of the endface of the polished fiber at the 14th experiment.

V. KRIGING INTERPOLATION AND OPTIMIZATION

The Kriging interpolation method is used herein to transform the discrete data of coupling efficiency into a continuous surrogate model of coupling efficiency. Kriging, named after the South Africa mining engineer D. C. Krige, is a geo-statistical interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown area. The Kriging surrogate model of the unknown function of interest $y(\mathbf{x})$ is as follows [24]:

$$\hat{y}(\mathbf{x}) = f(\mathbf{x}) + Z(\mathbf{x}) \quad (1)$$

where $f(\mathbf{x})$ is the known approximation (usually polynomial) function and $Z(\mathbf{x})$ is the realization of a stochastic process with mean zero, variance σ^2 , and nonzero covariance. $f(\mathbf{x})$ is regarded as a polynomial regression function, providing a “global” model of the design space. Because $f(\mathbf{x})$ approximates globally the design space, $Z(\mathbf{x})$ creates “localized” deviations so that the Kriging surrogate model interpolates the sampled data points. With the application of zero-order regression function and Gaussian correlation function, the Kriging surrogate model of the unknown function of interest can be re-built as follows:

$$\hat{y}(\mathbf{x}) = \hat{\beta} + \mathbf{r}^T(\mathbf{x})\mathbf{R}^{-1}(\mathbf{Y} - \mathbf{F}\hat{\beta}) \quad (2)$$

The vector $\mathbf{x} = \{x_1, x_2, \dots, x_p\}$ is a vector that is formed by the unknown input variables. The constant p is the number of the unknown input variables. The vector $\mathbf{r}(\mathbf{x})$ is the function of the unknown input variables that is determined by

$$\mathbf{r}(\mathbf{x}) = \{R_c(\mathbf{x}, \mathbf{x}_1), R_c(\mathbf{x}, \mathbf{x}_2), \dots, R_c(\mathbf{x}, \mathbf{x}_n)\}^T \quad (3)$$

where

$$R_c(\mathbf{x}, \mathbf{x}_i) = \prod_{m=1}^p \text{Exp}[-\theta_m(x_m - x_{im})^2], \quad i = 1, 2, \dots, n \quad (4)$$

$$\mathbf{x}_i = \{x_{i1}, x_{i2}, \dots, x_{ip}\}, \quad i = 1, 2, \dots, n \quad (5)$$

The constant n is the number of the sampled data points. The vector $\mathbf{Y} = \{y_1, y_2, \dots, y_n\}^T$ is a known response vector of the unknown function of interest $y(\mathbf{x})$. The vector $\mathbf{F}$ is a known column vector of length n that is filled with ones. The square matrix $\mathbf{R} = [R_{ij}]_{n \times n}$ is a known square matrix that is determined by

$$R_{ij} = \prod_{m=1}^p \text{Exp}[-\theta_m(x_{im} - x_{jm})^2], \quad i = 1, 2, \dots, n; \quad j = 1, 2, \dots, n \quad (6)$$

The constant $\hat{\beta}$ is a known constant that is determined by

$$\hat{\beta} = (\mathbf{F}^T \mathbf{R}^{-1} \mathbf{F})^{-1} \mathbf{F}^T \mathbf{R}^{-1} \mathbf{Y} \quad (7)$$

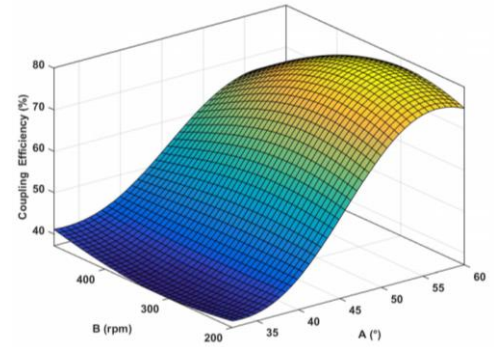


Fig. 5. The surface plot of coupling efficiency versus factors A and B.

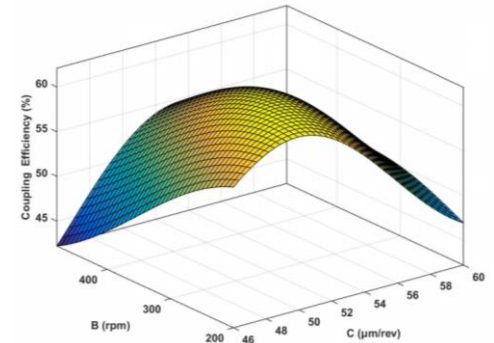


Fig. 6. The surface plot of coupling efficiency versus factors B and C.

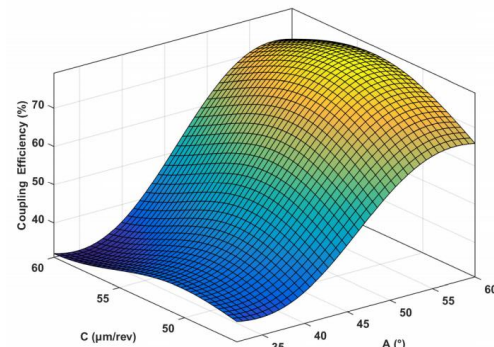


Fig. 7. The surface plot of coupling efficiency versus factors A and C.

Sacks *et al.* proposed a framework for the construction of Kriging surrogate models for deterministic outputs of expensive computer experiments [25]. In this study, the continuous surrogate model of coupling efficiency is created by applying DACE, a free Kriging interpolation MATLAB toolbox [26]. The surface plot of coupling efficiency versus factors A and B is created, as shown in Fig. 5. The surface

plot of coupling efficiency versus factors B and C is built, as shown in Fig. 6. The surface plot of coupling efficiency versus factors A and C is established, as shown in Fig. 7. It can be seen that the relationship between the coupling efficiency and the control factors is nonlinear. In other words, the coupling efficiency is a nonlinear function of control factors. The global effects plot for coupling efficiency is created, as shown in Fig. 8. It can be seen that the most important factor is A, polishing angle, the second important factor is C, feed rate, and the least important factor is B, rotation speed.

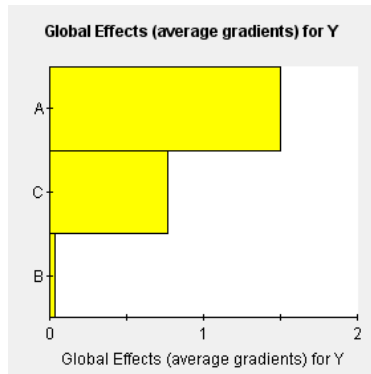


Fig. 8. The global effects plot for coupling efficiency.

To optimize the coupling efficiency, the continuous surrogate model of coupling efficiency is regarded as the objective function and the three control factors are regarded as the variables. A mixed algorithm combining a global search algorithm, genetic algorithm (GA), and a local search algorithm, Nelder-Mead simplex (NMS) algorithm, is applied to optimize the objective function. Figure 9 shows the flowchart of GA. The initial population of chromosomes is randomly generated from the design space formed by the control factors. With selection, crossover, and mutation operations, the population of chromosomes can be improved generation by generation. When the time to stop is reached, the best chromosome in the population of chromosomes is exported. Then, the best chromosome is the solution of control factors obtained by GA. Next, the solution of control factors obtained by GA is transferred to NMS algorithm to be the initial guess of solution of control factors. Figure 10 shows the flowchart of NMS algorithm [27]. The NMS algorithm, which is a commonly applied numerical method used to find the minimum or maximum of an objective function in a multidimensional space, is designed to solve the classical unconstrained optimization problems. Being a direct search method (based on function comparison), the NMS algorithm is often applied to nonlinear optimization problems for which derivatives may not be known.

By using the mixed algorithm that combines GA and NMS algorithm, the optimal solutions of control factors are obtained as shown in Table 4. The optimal polishing angle is 56° . The optimal rotation speed is 289 rpm. The optimal feeding rate is $52 \mu\text{m}/\text{rev}$. At this optimal design point, the optimum value of coupling efficiency is 79.63%. By using the SEM, the side and top views of the endface of the polished fiber at the optimal design point is as shown in Fig. 11. The comparison of coupling efficiencies in three different phases

is as shown in Table IV. After applying the uniform design of experiments method, the coupling efficiency is improved by 29.1%. After applying the Kriging interpolation and optimization methods, the improved rate of coupling efficiency is 30.8%. It can be found that the coupling efficiency can still get a lot of improvement even just using the uniform design of experiments method.

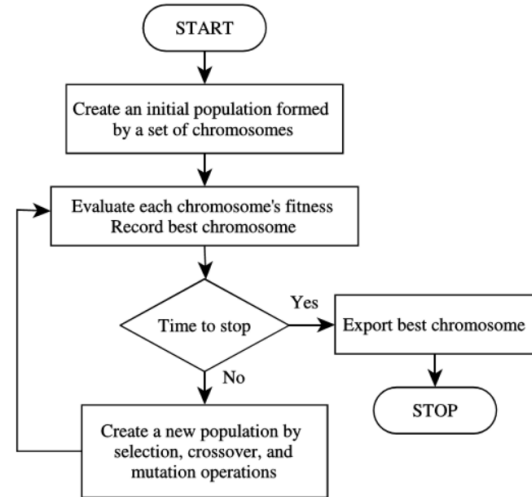


Fig. 9. The flowchart of GA.

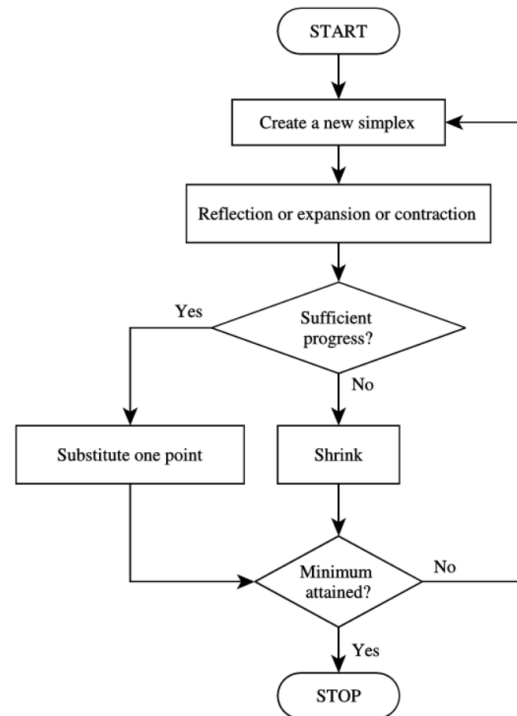
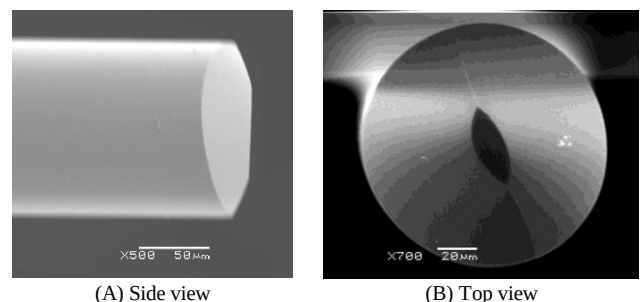


Fig. 10. The flowchart of NMS algorithm [27].



(A) Side view (B) Top view
Fig. 11. The side and top views of the endface of the polished fiber at the optimal design point.

TABLE IV: THE OPTIMAL SOLUTIONS OF CONTROL FACTORS

Factor	Meaning	Unit	Original	Optimal
A	Polishing angle	°	46	56
B	Rotation speed	rpm	340	289
C	Feed rate	μm/rev	53	52

TABLE V: COMPARISON OF THE COUPLING EFFICIENCIES IN THREE PHASES

Phase	Coupling efficiency (%)	Improved rate (%)
Original design	60.89	—
Best experiment point	78.61	29.1
Optimal design point	79.63	30.8

VI. CONCLUSION

This study has shown that the integration of the uniform design of experiments method, Kriging interpolation method, and optimization method can effectively maximize the coupling efficiency of the optical fiber lens with oval-shaped endfaces. To make the optical lens, a third-generation optical fiber endface polishing machine was applied firstly to polish the endfaces of optical fibers. Then, a type-36 optical fiber fusion splicer was used to fuse fibers into a lens. Polishing angle, feeding rate, and rotation speed were chosen as the control factors. The uniform design of experiments method was used to create a set of experiments that are uniformly scattered in the design space formed by the control factors. Kriging interpolation was applied to transform the discrete data of coupling efficiency into a continuous surrogate model of coupling efficiency. A mixed optimization algorithm, which combines GA and NMS algorithm, was used to maximum the continuous surrogate model of coupling efficiency. After optimization, the optimal design values of polishing angle, feeding rate, and rotation speed are 56°, 289 rpm, and 52 μm/rev, respectively, and the optimal coupling efficiency is 79.63%. Compared with the original value of coupling efficiency, the optimal coupling efficiency was improved by a rate of 30.8%. Furthermore, for coupling efficiency, the most important factor is polishing angle, the second important factor is feed rate and the least important factor is rotation speed.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Fangchen Dong and Chialing Hsieh conducted the experiments, analyzed the data and wrote the paper; Chengkang Lee guided the research process; all authors had approved the final version.

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Chialing Hsieh received a bachelor degree in electrical engineering from Yuan Zu University, Taiwan in 1997. She obtained her master degree in early childhood education from University of Central Oklahoma in 2000. Currently, she works as a lecturer in the Department of Industrial Engineering and Management, Cheng Shiu University, Taiwan. Her research interests are uniform design, Kriging interpolation and statistical analysis method.



Fangchen Dong received her bachelor and master degrees in mechanical engineering from Qingdao University of Science and Technology, Shandong, China in 2012. Currently, she works as a lecturer in the College of Mechanical and Electrical Engineering, Shandong Yingcai University, Shandong, China. Her research interests include polymer machinery and mechanical design.



Chengkang Lee received a bachelor degree in mechanical engineering from National Taiwan University of Technology, Taiwan in 1996. He obtained his Ph.D. degree in mechanical engineering from National Cheng Kung University, Taiwan in 2001. Currently, he works as a professor in Department of Industrial Engineering and Management, Cheng Shiu University, Taiwan. His research interests are design of experiments, optimization, mechanism and gear design, finite element analysis, and mechanical manufacturing.