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Abstract. This paper studies the effect of microlens front-face angle on the performance of an optical system consisting of a planar-graded refractive index (GRIN) lens pair facing each other separated by a free-space region. The planar silica microlens pairs are designed to facilitate low-loss optical signal propagation in the free-space region between the opposing optical waveguides. The planar lens is fabricated from a 38- μm -thick fluorine-doped silica layer on a silicon substrate. It has a parabolic refractive index profile in the vertical direction, which is achieved by controlled fluorine incorporation in the silica film to collimate the optical beam in the vertical direction. Horizontal beam collimation is achieved by incorporating a horizontal curvature at the front face of the lens defined by deep oxide etch. A generalized 3×3 *ABCDGH* transformation matrix method has been derived to compute the coupling efficiency of such microlens pairs to take front-face angles that may be present due to fabrication variations or limitations and possible input/output optical fiber offset/tilt into considerations. Pairs of such planar GRIN lens with various free-space propagation distances between them ranging from 75 to 2500 μm and with front-face angles of 1.5 deg, 2 deg, and 4 deg have been fabricated and characterized. Beam propagation method simulations have been carried out to substantiate the theoretical and experimental results. The results indicate that the optical loss is reasonably low up to 1.5 deg of front-face angles and increases significantly with further increase in the front-face angle. Analysis shows that for a given system with specific microlens front-face angle, the optical loss can be significantly reduced by properly compensating the vertical position of the input and output fibers. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMM.15.3.035501](https://doi.org/10.1117/1.JMM.15.3.035501)]

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1 Introduction

For over a decade, silica optical waveguides have been a key platform for the fabrication of photonic circuits and optical MEMS devices. Their relatively low refractive index contrast enables easier mode-field matching and alignment to optical fibers. In MEMS-based optical cross-connect switches,^{1–5} optical fibers with a collimating lens are often used to reduce the free-space propagation loss between the input and the output optical fibers. This approach, however, has limited the port count of optical switches. The use of planar waveguides in optical cross-connect architecture^{6–9} has been proposed and implemented to increase port counts and reduce the free-space propagation loss. However, these approaches require relatively complex fabrication processes involving the realization of the waveguide and the MEMS switch in separate substrates, which introduce alignment issues.⁵ Moreover, the free-space propagation loss is minimized by reducing the propagation distance between the planar waveguides. These existing drawbacks can be significantly mitigated by incorporating a planar microlens pairs.¹⁰ Other applications that can benefit from the development of such planar microlens pairs include free-space optical interconnects on chip.¹¹

The analysis of a planar microlens pair that allows low-loss free-space transmission of light between two opposing

waveguides/fibers has been reported^{12,13} for potential applications in optical cross-connect switches and optical interconnects. In Ref. 13, a 2×2 *ABCD* matrix method for designing and computing the coupling efficiency of optical systems comprising planar microlens pair was developed. This analysis was based on the assumption that the components in the optical system are in alignment with the axis of light propagation that has a perfectly vertical microlens front face and properly aligned input/output optical fibers at the input/output butt-coupling ends. Although achieving a perfectly vertical front face in the lens is highly desirable, fabricated angles can be slightly off the vertical axis and hence introduce front-face angle. Moreover, lateral and/or angular offset can be present in the fibers at the input/output butt-coupling ends. Such small deviations from perfect verticality at the lens front faces and lateral and/or angular offset in the fibers at the input/output butt-coupling ends can introduce the substantial optical loss. However, previously reported works made no provision to accommodate such effects in the optical loss analysis and the fabricated device. In this paper, we report on an optical analysis approach based on a generalized 3×3 *ABCDGH* transfer matrix method that takes the effect of front-face angle deviation from vertical and input/output optical fiber offset/tilt on the performance of planar graded refractive index (GRIN) lens-based optical

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system into consideration. The theoretical work is substantiated by beam propagation method (BPM) simulation and experimental results.

The presentation of the paper is as follows. Section 2 describes the design methodology and coupling efficiency calculation of a planar microlens-based optical system using 2×2 ABCD and 3×3 ABCDGH transfer matrix methods. This will be followed by the fabrication procedure for the lens pair system designed for an ideal free-space propagation distance of $1000 \mu\text{m}$ with various front-face slopes in Sec. 3. Comparison between theory, simulation, and experimental results of the performance of microlens pairs is given in Sec. 4, followed by the conclusion in Sec. 5.

2 Design Methodology

The evolution of the Gaussian input spot size, ω_0 , as it propagates through the planar microlens pair and the free space between them is shown schematically in Figs. 1(a) and 1(b). With the beam propagating in the z -direction, focusing in the x - and y -directions is achieved by the GRIN silica film and the front-face curvature of the lens as shown in Figs. 1(a) and 1(b), respectively. The design parameters for the microlens system, as indicated in Fig. 1(a), are: d_T is the free-space propagation distance, ω_0 is the input spot size of the Gaussian beam, and ω_{cx} is the vertical spot size at midpoint of the free-space propagation region. The GRIN profile of silica film is defined by $n(x) = \{n_0^2[1 - 2\Delta(x/\rho)^2]\}^{1/2}$, where $\Delta = (n_0^2 - n_{cl}^2)/2n_0^2$ is the relative index change, x is the transverse (vertical) coordinate, and n_0 , n_{cl} , and ρ are the maximum refractive index, minimum refractive index, and half-width of the graded index profile, respectively. Thus, the critical input parameters required for the microlens pair design are n_0 , Δ , wavelength λ , ω_0 , ω_{cx} ,

Fig. 2 Design flowchart.

and d_T . Figure 2 shows the flowchart of the iterative algorithm for the microlens pair design procedure for the ideal free-space propagation distance, d_T , with the zero optical loss. From these input parameters, other parameters that can be calculated are: (i) the horizontal spot size at the microlens/air interface, ω_{iy} , (ii) the horizontal spot size at midpoint of the free-space propagation distance, ω_{cy} , (iii) maximum vertical spot size in the microlens section, ω_{mx} , (iv) radius of curvature defining the convex shape, R , (v) microlens length, L , (vi) focusing parameter, $\alpha = \sqrt{2\Delta/\rho}$, (vii) minimum refractive index of the graded index profile, n_{cl} , and (viii) half-width of the parabolic graded index profile, ρ .

Fig. 1 Schematic diagram of a planar silica microlens pair with input and output fibers: (a) side view and (b) top view, showing the Gaussian beam evolution in the microlens pair and in the free space.

Figure 2 succinctly captures the design flow algorithm in determining the critical microlens pair physical dimensions (L , ρ , R) and important beam waist parameters (ω_{mx} , ω_{iy} , and ω_{cy}) using the 2×2 $ABCD$ matrix method in the vertical and horizontal directions. Based on this approach, a planar microlens pair optimized for $d_T = 1000 \mu\text{m}$ has been designed and the results are tabulated in Table 1. Note that the design procedure of microlens system does not take the front-face angles and/or butt-coupling ends fiber offsets into account. However, the optical loss calculation should consider all the possible physical variations to produce a complete analysis. This requires extension of the 2×2 $ABCD$ matrix method to the generalized 3×3 $ABCDGH$ transfer matrix method that will be explained Sec. 2.1.

2.1 Optical Loss Analysis by 3×3 $ABCDGH$ Transfer Matrix Method

An optical system comprising of input/output optical fibers and planar silica microlens pair with nonvertical front-face angles is schematically shown in Fig. 1. The optical fibers are butt-coupled with the planar silica lens pair for launching and receiving an optical beam at their respective ends. The front-face angles at the first and the second lens are designated by θ_1 and θ_2 , respectively, as angular deviation from the ideal 90 deg. They can be caused by fabrication variations/limitations during the deep oxide etch to define the front-face curvature. Optical coupling efficiency calculations that take into account the front-face slope and fiber butt-coupling ends offset can be accommodated by a 3×3 $ABCDGH$ transfer matrix method. The 3×3 $ABCDGH$ matrix elements for individual components and interfaces in the vertical plane of the optical system [Fig. 1(a)] are as follows:

$$M_{12} = M_{56} = \begin{pmatrix} \cos(\alpha L) & \frac{\sin(\alpha L)}{\alpha} & 0 \\ -\alpha \sin(\alpha L) & \cos(\alpha L) & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (1)$$

between planes 1 to 2 and 5 to 6,

$$M_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & n_0 & 0 \\ \frac{2\pi(n_0-1)\tan\theta_1}{\lambda} & 0 & 1 \end{pmatrix} \quad (2)$$

at the interface of planes 2 to 3,

$$M_{34} = \begin{pmatrix} 1 & d_T & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3)$$

between planes 3 to 4,

$$M_{45} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{n_0} & 0 \\ \frac{2\pi(n_0-1)\tan\theta_2}{\lambda} & 0 & 1 \end{pmatrix} \quad (4)$$

at the interface of planes 4 to 5

The effective 3×3 $ABCDGH$ matrix elements of the total system in the vertical plane between planes 1 and 6 [in Fig. 1(a)] can be obtained as follows:

$$A_x = \cos(\alpha L)^2 - \left[d_T \cos(\alpha L) + \frac{\sin(\alpha L)}{\alpha n_0} \right] n_0 \alpha \sin(\alpha L), \quad (5)$$

$$B_x = \frac{\cos(\alpha L) \sin(\alpha L)}{\alpha} - \left[d_T \cos(\alpha L) + \frac{\sin(\alpha L)}{\alpha n_0} \right] n_0 \cos(\alpha L), \quad (6)$$

$$C_x = -\alpha \sin(\alpha L) \cos(\alpha L) - \left[-d_T \alpha \sin(\alpha L) + \frac{\cos(\alpha L)}{n_0} \right] n_0 \alpha \sin(\alpha L), \quad (7)$$

$$D_x = -\sin(\alpha L)^2 + \left[-d_T \alpha \sin(\alpha L) + \frac{\cos(\alpha L)}{n_0} \right] n_0 \cos(\alpha L), \quad (8)$$

$$G_x = \left[\frac{2\pi(n_0-1)\tan(\theta_2)}{\lambda} + \frac{2\pi(n_0-1)\tan(\theta_1)}{\lambda} \right] \cos(\alpha L) - \frac{2\pi(n_0-1)\tan(\theta_2)d_T n_0 \alpha \sin(\alpha L)}{\lambda}, \quad (9)$$

$$H_x = \frac{\left[\frac{2\pi(n_0-1)\tan(\theta_2)}{\lambda} + \frac{2\pi(n_0-1)\tan(\theta_1)}{\lambda} \right] \sin(\alpha L)}{\alpha} + \frac{2\pi(n_0-1)\tan(\theta_2)d_T n_0 \cos(\alpha L)}{\lambda}. \quad (10)$$

Table 1 (a) Design parameters and (b) calculated parameters for the microlens pair designed for $d_T = 1000 \mu\text{m}$.

(a) Design parameters							
d_T	Λ	Δ	n_0	ω_0	ω_{cx}		
1000 μm	0.633 μm	0.01	1.40	2.15 μm	10.3 μm		
(b) Calculated parameters							
ω_{iy}	ω_{cy}	ω_{mx}	R	L	$\alpha = \sqrt{2\Delta}/\rho$	n_{cl}	ρ
24.76 μm	24.4 μm	14.36 μm	104.56 μm	368.5 μm	$4.66 \times 10^{-3} \mu\text{m}^{-1}$	1.386	30.33 μm

Similarly, the effective 3×3 $ABCDGH$ matrix elements of the total system in the horizontal plane as shown in Fig. 1 (b) between planes 1 and 6 can be from matrix elements for individual components and interfaces in the horizontal plane and shown to be as follows:

$$A_y = 1 + \frac{L(1-n_0)}{n_0 R} + \frac{\left[\left(1 + \frac{L(1-n_0)}{n_0 R} \right) d_T + \frac{L}{n_0} \right] (1-n_0)}{R}, \quad (11)$$

$$B_y = \left\{ 1 + \frac{L(1-n_0)}{n_0 R} + \frac{\left[\left(1 + \frac{L(1-n_0)}{n_0 R} \right) d_T + \frac{L}{n_0} \right] (1-n_0)}{R} \right\} L + \left[\left(1 + \frac{L(1-n_0)}{n_0 R} \right) d_T + \frac{L}{n_0} \right] n_0, \quad (12)$$

$$C_y = \frac{(1-n_0)}{n_0 R} + \frac{\left[\frac{(1-n_0)d_T}{n_0 R} + \frac{1}{n_0} \right] (1-n_0)}{R} \quad (13)$$

$$D_y = \left\{ \frac{(1-n_0)}{n_0 R} + \frac{\left[\frac{(1-n_0)d_T}{n_0 R} + \frac{1}{n_0} \right] (1-n_0)}{R} \right\} L + \left[\frac{(1-n_0)d_T}{n_0 R} + \frac{1}{n_0} \right] n_0, \quad (14)$$

$$G_y = 0, \quad (15)$$

$$H_y = 0. \quad (16)$$

Both the 3×3 $ABCDGH$ matrices of the total optical system in the vertical and horizontal planes will be used to determine important beam parameters required for the overall coupling efficiency calculation.

At plane 1 in Fig. 1, the light beam coming out of a single-mode fiber end is known to have a Gaussian intensity profile that can be represented by the following expression:^{14,15}

$$\psi_f = \exp \left[- \left(\frac{x^2 + y^2}{\omega_0^2} \right) \right]. \quad (17)$$

Similarly, the modal field of the optical beam at the receiving end of the optical system at plane 6 in Fig. 1 can be expressed as

$$\psi_v = \exp \left[- \left(\frac{x^2}{\omega_{2x}^2} + \frac{y^2}{\omega_{2y}^2} \right) \right] \exp \left[- \frac{jk_2}{2} \left(\frac{x^2}{R_{2x}} + \frac{y^2}{R_{2y}} \right) \right], \quad (18)$$

where $k_2 = 2\pi n_0/\lambda$ is the wave number in the medium. Now by employing the vertical and horizontal axis $ABCDGH$ matrix parameters for the total optical system, the final spot sizes ω_{2x}, ω_{2y} and the radii of curvatures R_{2x}, R_{2y} of the wave front at plane 6 can be determined. The coupling

efficiency of such an optical system can, then, be calculated by the overlapping integral of these two fields at plane 6 of Fig. 1 and can be expressed as in Refs. 16 and 17

$$\eta = \eta_x \eta_y, \quad (19)$$

where

$$\eta_x = \eta_{zx} \eta_{dx} \eta_{\theta_x}, \quad (20)$$

$$\eta_{zx} = \frac{2}{\omega_0 \omega_{2x} \sqrt{\left(\frac{1}{\omega_0^2} + \frac{1}{\omega_{2x}^2} \right)^2 + \frac{k_2^2}{4R_{2x}^2}}},$$

$$\eta_{dx} = \exp \left\{ -2d_x^2 \left[\frac{\left(\frac{1}{\omega_0^2} + \frac{1}{\omega_{2x}^2} \right) + \frac{k_2^2}{4\omega_0^2 R_{2x}^2}}{\left(\frac{1}{\omega_0^2} + \frac{1}{\omega_{2x}^2} \right)^2 + \frac{k_2^2}{4R_{2x}^2}} \right] \right\}, \quad (21)$$

$$\eta_{\theta_x} = \exp \left\{ -\frac{k_2^2 \theta_x^2}{2} \left[\frac{\left(\frac{1}{\omega_0^2} + \frac{1}{\omega_{2x}^2} \right)}{\left(\frac{1}{\omega_0^2} + \frac{1}{\omega_{2x}^2} \right)^2 + \frac{k_2^2}{4R_{2x}^2}} \right] \right\}, \quad (22)$$

$$\eta_{dx, \theta_x} = \exp \left\{ k_2^2 d_x \theta_x \left[\frac{\left(\frac{1}{R_{2x} \omega_0^2} \right)}{\left(\frac{1}{\omega_0^2} + \frac{1}{\omega_{2x}^2} \right)^2 + \frac{k_2^2}{4R_{2x}^2}} \right] \right\}. \quad (23)$$

Similarly, the expression of η_y is obtained by replacing x in Eqs. (20)–(23) with y . Coupling efficiencies η_x and η_y represent the contributions from the x - and y -directions. η_{zx} is the coupling efficiency from x -direction without any misalignments. η_{dx} and η_{θ_x} are the coupling efficiencies with misalignments resulting from an axial offset d_x and a tilt θ_x , respectively, and η_{dx, θ_x} indicates the combined effect of axial offset and tilt.

To calculate the coupling efficiency of the microlens-based optical system, the tilt and offset terms in Eqs. (21)–(23) will need to be obtained. Let us define the position and slope of the Gaussian input beam amplitude center in the vertical direction (x) at plane 1 in Fig. 1(a) as d_{ax1} and d'_{ax1} , respectively. Using the 3×3 $ABCDGH$ matrix element of the optical system in the x -direction, the position and slope of the output optical beam amplitude center at plane 6 in Fig. 1(a) can be related to d_{ax1} and d'_{ax1} as follows:^{18,19}

$$d_{ax2} = A_x d_{ax1} + B_x d'_{ax1} + \frac{\lambda(B_x G_x - A_x H_x)}{2\pi n_0}, \quad (24)$$

$$d'_{ax2} = C_x d_{ax1} + D_x d'_{ax1} + \frac{\lambda(D_x G_x - C_x H_x)}{2\pi n_0}, \quad (25)$$

where d_{ax2} and d'_{ax2} are position and slope of the output optical beam amplitude center at plane 6, respectively. Defining the vertical position and slope of the output single-mode optical fibers at plane 6 in Fig. 1(a) as d_{ax3} and d'_{ax3} , the tilt, θ_x , and offset, d_x , can be calculated as $\theta_x = d'_{ax2} - d'_{ax3}$ and $d_x = d_{ax2} - d_{ax3}$, respectively. Using these tilt and offset values in Eqs. (21)–(23), the coupling coefficient of the optical

system in the vertical direction (x) can be evaluated. A similar process has been employed to evaluate the optical loss in the horizontal direction. It is important to note that using the reformulated 3×3 $ABCDGH$ transfer matrix method, individual loss contribution from input/output optical fiber tilt and offset, both in the vertical and horizontal directions, as well as microlens front-face slopes can be evaluated, which was not possible with the previous approach in Ref. 13.

2.2 Theoretical Analysis and Beam Propagation Method Simulation

The optical loss results obtained from the 3×3 $ABCDGH$ transfer matrix method developed in Sec. 2.1 are compared with the results obtained from the BPM simulation (BPM_CAD, Optiwave). The system under study is designed for an ideal free-space propagation distance, $d_T = 1000 \mu\text{m}$ with the design and calculated parameters provided in Tables 1(a) and 1(b), respectively. Figure 3 shows the theoretical and simulation results of the optical loss due to axial offset in the input or the output optical fiber at the respective butt-coupling end. Due to the symmetric Gaussian beam profile, both the vertical and the horizontal axial offset for a single optical fiber (input/output) will produce the same amount of optical loss. However, when both the input and the output fibers are axially offset by the same amount (and in the same direction), the loss is higher in the horizontal direction than in the vertical. Similar conclusions could be drawn for the effect of tilt angles in the input/output fibers on the optical loss as shown in Fig. 4. Around 1 dB of loss would be incurred for a single fiber axial offset of $1 \mu\text{m}$ or tilt of 2 deg. In all the cases, the BPM simulation results are well matched with the theoretical results. Note that the system is more sensitive toward axial offset than tilt angles as shown in Figs. 3 and 4. Also, the optical system is more sensitive to horizontal direction axial offset or tilt when both input and output fibers are misaligned by the same amount (and in the same direction) compared with the vertical direction due to the larger spot size of the optical beam in the horizontal axis. Figure 5 shows the theoretical and simulation results of the optical loss due to single and both microlens front-face slopes. The loss due to individual microlens front-face slope is identical to each other, whereas the loss due to both the microlens front-face slopes is almost twice of the loss for a single microlens front-face slope. Figure 6

Fig. 3 Theoretical and BPM simulation results of optical loss due to input/output fiber axial offsets.

Fig. 4 Theoretical and BPM simulation results of optical loss due to input/output fiber tilt angles.

shows the theoretical and simulated optical loss due to both the microlens front-face slopes varied from 0 deg to 2 deg for various free-space propagation distances ranging from 75 to $2500 \mu\text{m}$. As expected, the minimum loss occurs at the ideal free-space propagation distance of $1000 \mu\text{m}$ for any microlens front-face slopes and increases with the decrease or increase in the free-space propagation distance from the ideal $1000 \mu\text{m}$. To investigate the effect of axial offset in the input/output optical fibers in the presence of microlens front-face slopes, let us consider the system that is designed for an ideal free-space distance of $d_T = 1000 \mu\text{m}$, where the microlens front-faces have a slope of 4 deg. The input and output optical fiber axial positions are varied vertically downward by the same amount, and the corresponding optical losses are computed theoretically and by simulation. The results are plotted in Fig. 7. It is found that if both input and output fibers are offset downward vertically by around $4.5 \mu\text{m}$, the loss is reduced to around 0.05 dB from 35.6 dB. This shows that the loss due to both the microlens front-face slopes can be compensated by properly offsetting the input and output fibers.

It is worth mentioning that although we have used 633 nm as the optical wavelength for this study, the design methodology and optical loss analysis presented here is equally applicable for other wavelengths as well. One has to properly select relevant design parameters, such as optical fiber spot size for a specific wavelength, free-space propagation distance, refractive index step-size, and front-face-curvature,

Fig. 5 Theoretical and BPM simulation results of optical loss due to various microlens front-face slopes.

Fig. 6 Theoretical and BPM simulation results of optical loss due to varying microlens front-face slopes with different free-space propagation distances.

Fig. 7 Theoretical and BPM simulation results of optical loss due to varying input and output fiber axial offset (the same amount in the same direction) in the presence of microlens front-face slopes of 4 deg for an ideal system designed for $d_T = 1000 \mu\text{m}$.

for designing a planar microlens for any other optical wavelength than 633 nm. Moreover, it is important to indicate that the ideal low-loss free-space propagation distance of $1000 \mu\text{m}$ used in this study is to consider a stack die system with two wafers each having a thickness of $500 \mu\text{m}$. However, this does not restrict its applicability or the design approach for any other potential applications and free-space propagation distances.

In Sec. 3, we discuss the fabrication procedure for microlens pairs with varying front-face slopes and compare the experimental results against the theoretical results to validate the theoretical analysis.

3 Graded Refractive Index Microlens Fabrication

The fabrication procedures for GRIN silica microlens have been described previously.^{20,21} However, those fabrication steps were not developed to control the front-face angle of the GRIN silica microlens and form U-groove that allows the offset positioning of input and output optical fibers. To experimentally substantiate the theoretical analysis discussed in Sec. 2.2, the fabrication process need to be modified to allow the aforementioned features. Therefore, here we describe the modified fabrication procedure. The scanning electron microscopy (SEM) image of the fabricated GRIN microlens pairs with various free-space propagation

distances between them is shown in Fig. 8(a). The fabrication process steps along A–A' are shown in Fig. 8(b). The U-shaped grooves for optical fibers insertions are incorporated into the process to allow downward offsetting of the vertical position of the optical fibers. The process starts with a 4" P-type Si (100) wafer as a substrate. Fluorine-doped silicon oxide ($\text{Si}_x\text{O}_y\text{F}_z$) films are deposited using a hollow cathode plasma-enhanced chemical vapor deposition (HC-PECVD) system from a mixture of $\text{SiH}_4/\text{O}_2/\text{CF}_4$ gases. The first step in the deposition schedule is to deposit a $4\text{-}\mu\text{m}$ -thick buffer layer to minimize any optical leakage to the silicon substrate. This deposition is done at a CF_4 flow rate of 39.3 sccm, 300 W radio frequency (RF) power, 100 sccm of O_2 , and 15 sccm of SiH_4 to obtain a refractive index of 1.38. Note that at this CF_4 flow rate, the F-doped silica film shows a slight tensile stress that would be useful for reducing the overall stress of the thick film deposited subsequently. The second step is to deposit a $32\text{-}\mu\text{m}$ -thick-graded index silica film with the required parabolic profile. For this step, oxygen and silane flow rates are fixed at 100 and 15 sccm, respectively, and the CF_4 flow rate is varied from 25 to 29.3 sccm at 300 W RF power and 10 mTorr of pressure to change the refractive index from 1.4 to 1.393. The parabolic refractive index profile for the microlens pair designed for a free-space propagation distance of $1000 \mu\text{m}$ is approximated in a stepwise fashion with index steps of 0.0005. Such index steps are chosen to ensure the relatively low optical loss ($<0.5 \text{ dB}$).²² The periodic refocusing characteristic of such graded index silica film has been experimentally confirmed with a fluorescence technique described in Ref. 21. In the last step of the deposition process, the CF_4 gas is taken off from the plasma that allows a pure silica capping layer to be deposited on top of the graded index film. The capping layer serves to prevent moisture absorption from the ambient during device characterization. The measured final film thickness and residual stress of the film are $38 \mu\text{m}$ and 16 MPa, respectively, determined from wafer curvature measurements.²³ The same HC-PECVD system is used to deposit a $5\text{-}\mu\text{m}$ -thick amorphous silicon layer on top of the silica film using a mixture of 60 sccm of Ar and 6 sccm of SiH_4 at an RF power of 300 W and pressure of 4 mTorr. The deposited amorphous silicon film is then photolithographically patterned using photoresist. The amorphous silicon is etched with SF_6 and C_4F_8 chemistry in an surface technology systems inductively coupled plasma advanced oxide etch system using the photoresist as a mask.

The patterned amorphous silicon is then used as the mask for etching the thick silica film in the same system. Three different recipes have been used to obtain the microlens with different front-face slopes. C_4F_8 and He flow rates are fixed at 18 and 300 sccm, respectively, for all the three different recipes. The coil power is fixed at 1400 W and pressure maintained at 6 mTorr for all the experiments. Only the platen power is varied to achieve different front-face slopes. Planar lens with front-face angles of 1.5 deg at 400 W platen power, 2 deg at 300 W platen power, and 4 deg at 200 W platen power have been fabricated. Figures 9(a)–9(c) show SEM cross-sectional views of the fabricated front-face angles. Slight ruggedness observed on the cross-sectional views in Fig. 9 is due to the quality of mechanical cleaving rather than the process condition. Cleaving may also leave

Fig. 8 (a) SEM image of the fabricated microlens and (b) fabrication process flow.

Fig. 9 SEM cross-sectional views of the fabricated front-face angles (a) 1.5 deg, (b) 2 deg, and (c) 4 deg.

debris behind. The burr on the cross-sectional view in Fig. 9(a) is the result of that.

While the fabrication process can be tuned to produce vertical angles within a tolerance of ± 0.2 deg, the front-face slopes for measurements are chosen to be larger in magnitude and incremental steps than the tolerance limit and also taking into account the little influence that nearly vertical slopes have on the optical loss.

After the silica etching step, the sample is treated in oxygen plasma for 15 min to remove any polymer formed during the deep oxide etch. The sample is then deep reactive ion etching etched using silica as a mask to form the U-grooves in the silicon substrate for fibers butt-coupling.

It should be mentioned that surface roughness in the microlens front face is mainly due to the line edge roughness of the mask pattern used to define the lens face. The line edge roughness depends in turn on the photolithography process employed to pattern the photoresist and is expected to be less than the optical wavelength (633 nm); hence, it will have minimal contribution to the overall loss in the system.

4 Optical Testing and Discussion

The schematic diagram of the experimental setup for characterizing the planar silica microlens pair is shown in Fig. 10. The input and output optical fibers are placed into the U-grooves and butt-coupled to the microlens pair. A 633-nm optical signal from a pigtailed laser source is coupled

with the input fiber while the power at the output optical fiber is measured. Initially, the power at the output of the input fiber is measured to be used as a reference power to calculate the optical loss in the system.

To evaluate the performance of the microlens pair with front-face slopes, various free-space propagation distances were fabricated, apart from the ideal free-space propagation distance of 1000 μm . The theoretical, simulation, and measured optical losses for the microlens pairs with front-face slopes of 2 deg at each microlens are plotted in Fig. 11 for free-space propagation distances of 75, 275, 500, 1000, 1500, 2000, and 2500 μm .

Note that the theoretical and simulation results do not take into account the reflection losses of 0.12 dB at each microlens/air interface. One can see, from Fig. 11, that the average difference between the theoretical/simulation and experimental results is around 3 dB. Such disparities can be attributed to the following in addition to interface losses: (i) misalignment at the butt-coupling ends during the measurement, (ii) limitation of thick silica film in collecting expanded optical beam where the free-space distances are longer than the ideal design value of 1000 μm , (iii) stepwise index change of films to approximate the required parabolic index profile, (iv) scattering due to roughness at the vertical front-face of the microlens, (v) deviation of the horizontal front-face curvature from the designed value as a result of the pattern transfer process during fabrication, and (vi) the

Fig. 10 Schematic of the optical test setup.

Fig. 11 Free-space propagation losses with identical microlens pairs (front-face slope of 2 deg) with various free-space propagation distances.

propagation loss in the silica slab. Also, note that either input or output fiber axial offset of $1 \mu\text{m}$ or angular misalignment of 2 deg (vertical or horizontal direction) can contribute ~ 1 dB in the overall loss. Considering the various possible sources of loss, it can be stated that reasonable agreement between the theoretical, simulation, and experimental results has been achieved. Also from Fig. 11, it can be observed that the microlens pair is best suited for $1000 \mu\text{m}$ of free-space propagation distance for which it is designed. The major contributor to loss at the ideal free-space propagation distance is the existence of front-face angle. The optical losses at such ideal free-space propagation distance are measured for three different front-face slopes and plotted in Fig. 12. Although there is some difference between the theoretical and experimental results, the trend in the experimental data follows that of the theoretical analysis. From Figs. 3 and 12, one

 Fig. 12 Theoretical, simulation, and measured at $1000 \mu\text{m}$ free-space propagation distance for various front-face slopes.

can see that the losses due to front-face slopes are acceptable up to 1.5 deg and above 1.5 deg the loss increases significantly as the slope increases. We measured ~ 30 dB optical loss for a microlens pair with front-face slopes of 4 deg. This can be attributed to the possible reduction in the optical loss as a result of the input and output optical fiber vertical offsets during the experiment as demonstrated through simulation and theoretical analysis previously in Fig. 7.

5 Conclusion

We have developed a 3×3 *ABCDG* transfer matrix method to theoretically evaluate the performance of optical systems comprising of microlens pair with front-face slopes and verified against BPM simulation and experimental results. It was shown that each lens front-face slope contributes equally to the optical loss and total loss due to both the lens front-face slopes are almost twice that of a single lens front-face slope. Also, the loss due to microlens front-face slopes can be compensated by properly offsetting the input and output fibers vertically.

The fabrication procedure to achieve GRIN microlens pair with nonvertical front-face has been described. Microlens pairs designed for an ideal free-space propagation distance of $1000 \mu\text{m}$ with front-face slopes of 1.5 deg, 2 deg, and 4 deg have been fabricated. The optical loss was found to be minimal for up to 1.5 deg of microlens front-face slope and increases significantly after that. The developed analytical method in this paper can be used as an accurate and fast examination tool for the performance evaluation of such optical systems as substantiated by BPM simulation and experimental results.

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