Subwavelength on-chip light focusing with bigradient all-dielectric metamaterials for dense photonic integration

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Abstract
Photonic integrated circuits (PICs) provide a promising platform for miniaturized on-chip optical systems for communication, computation, and sensing applications. The dense integration of photonic components is one of the keys to exploit the advantages of PIC. Although light focusing is a fundamental and indispensable function in PICs, focusing light at the micro/nanometer-scale is challenging. Here, a bigradient on-chip metalens (BOML) is proposed to achieve ultrasmall focal lengths and spot sizes at the subwavelength scale for dense PICs. The design of BOML combines gradient geometry and gradient refractive index into one metalens by simultaneously engineering the length and width of subwavelength silicon slots. With a small device footprint of only 168 μm, the BOML achieves efficient on-chip focusing with the record-breaking figure-of-merits, which are the ratio of wavelength to focal length/spot size (0.268 and 2.83) and numerical aperture (1.78). Leveraging on the Fresnel design, the footprint of BOML is further reduced by 55.1%, and the numerical aperture is enhanced to 1.9. The demonstration of mode conversion and beam steering with efficiency over 80% and a tilting range of 7.2° holds the potential for highly dense on-chip photonic systems for optical communication, optical sensing, nonlinear optics, and neural networks for deep learning.

KEYWORDS
all-dielectric metamaterials, beam steering, mid-infrared, on-chip focusing, photonic integrated circuits

1 | INTRODUCTION

In the past decades, photonic integrated circuits (PICs) have shown exceptional advantages on on-chip dense integration for state-of-the-art applications, including ultrasensitive physical and chemical sensing1-5 high-speed data communication,6-9 programmable photonics10-12 and photonic neural networks (PNNs).13-15 Light focusing is an essential and fundamental function in all-optical systems, including PICs. However, the current approach to focus light in PICs is to use adiabatic waveguide tapers with hundreds of microns in length,16,17 which leads to a waste of
PIC footprint. Due to the requirement of dense integration of PICs, light focusing needs to be achieved in a confined area for efficient light routing. In particular, a photonic device that has an ultrasmall focal length (f) and spot size (s) at the subwavelength scale is desired to focus light into a small spot efficiently (e.g., a waveguide whose width is less than half of the wavelength) within a short propagation distance.\(^{18,19}\)

An intuitive solution to achieve compact light focusing on PICs is to miniaturize traditional lenses, which are able to focus light efficiently. Traditional lenses are enabled by gradient geometries (spherical, parabolic, or Fresnel lenses) and gradient refractive index.\(^{20}\) Yet, they are challenging to implement in PICs due to the fabrication difficulty at the nanoscale. Alternatively, metamaterials could be a solution because they have great light manipulation capability and can be easily fabricated at the nanoscale. Metamaterials are artificial structures with engineered subwavelength unit cells to perform flexible and effective manipulation of amplitude, phase, and polarization of electromagnetic (EM) waves,\(^{21–24}\) giving rise to various applications like propagation manipulation,\(^{25,26}\) polarization detection,\(^{27,28}\) hologram,\(^{29}\) cloaking,\(^{30}\) logic operation,\(^{31}\) spectrometer,\(^{32}\) and imaging for virtual reality.\(^{33}\) With the various tuning methods, metamaterials also achieve dynamic manipulation of EM waves or perform multifunctional meta-devices by different tuning states.\(^{34–37}\) As a unique form of metamaterials, metalenses can leverage the phase profile generated by different metamaterials unit cells to achieve focusing, beam expansion, and imaging.\(^{38–40}\) Currently, metalenses are commonly designed for free-space optics to focus light through artificially engineering-enabled phase modulation.\(^{41}\)

Several approaches based on on-chip metalens (OML) have been proposed for ultra-compact light focusing in PICs.\(^{42–45}\) The two major types are gradient refractive index OML (GRIN-OML) and gradient geometry OML (GG-OML), both of which can control the phase profile of light propagating in waveguides. Plasmonic nanoantennas (PNAs) were first used to control the phase profile by manipulating the gradient refractive index. Upon the integration of PNA-based OML with waveguide, the guided light triggers localized surface plasmon resonance (LSPR) at the PNA/waveguide interface.\(^{42}\) With the gradient refractive index originating from the length-graded PNA structures, the phase profile along the light propagation direction is tailored to the parabolic profile for in-plane focusing. However, the high insertion loss caused by the ohmic loss of gold (Au) nanorods ruins the efficiency of metalenses (see Section S1 in supporting information for a detailed benchmark). To address the high insertion loss issue, all-dielectric metamaterials are introduced to achieve on-chip focusing by manipulating the gradient refractive index.\(^{43}\) In contrast to PNAs that operate in resonant modes, the all-dielectric metamaterials operate in guided modes, resulting in broadband operation and lossless focusing.\(^{44,45}\) Besides the gradient refractive index, the phase profile can also be controlled by gradient geometry to realize light focusing.\(^{46,47}\) However, the focal lengths achieved by either GRIN-OML or GG-OML are still one order larger than wavelengths because the two types are usually studied independently.

Mid-infrared (MIR) photonics has become an attractive research topic thanks to the extraordinary performance of spectroscopic chemical sensing by molecular-specific fingerprint absorption.\(^{48–50}\) Multiple material platforms have been developed to fabricate photonic waveguides and other functional building blocks.\(^{51}\) Additionally, on-chip spectroscopic sensing using waveguides in MIR has been demonstrated by detecting molecular vibrational absorption fingerprints.\(^{52,53}\) Furthermore, complex integration with multiple photonic components, light sources,\(^{55}\) detectors,\(^{56}\) and microfluidics\(^{57}\) or gas channels\(^{58}\) boosts the system performance for MIR spectroscopic chemical sensing. However, toward the dense integration of MIR photonic systems with multiple sensing channels and optical components, there is still a lack of OML developed for effectively focusing MIR light on compact footprints. Moreover, the two defined critical figure-of-merits (FOMs) in evaluating the focusing effect of OMLs, which are normalized focal length (λ/f) and spot size (λ/s), must be improved toward subwavelength ranges. The reason to use wavelength-normalized focal length and spot size is that the cross-sectional waveguide sizes and functional subwavelength structures (e.g., photonic crystals,\(^{59}\) subwavelength gratings,\(^{74}\) etc.) are highly dependent on wavelength due to the guiding mode requirement. Thus, the focusing requirements on waveguide systems are varying from wavelengths.

In this work, we study the relevance between the GRIN-OML and GG-OML and demonstrate that combining the two types will lead to an enhanced third type (big-gradient on-chip metalens [BOML]) with ultrasmall focal lengths and spot sizes at the subwavelength scale. The BOML consists of 11 air slots with synergistic gradient geometry and gradient refractive index to optimize the phase profile. At the working wavelength of 3.7 μm, the BOML achieves efficient on-chip focusing with a focal length of 13.8 μm and a spot size of 1.308 μm. As this work is the first OML in the mid-infrared to the best of our knowledge, we defined the wavelength-normalized focal length (λ/f) and spot size (λ/s) to provide a fair comparison to the near-infrared (NIR) counterparts. The corresponding λ/f and λ/s values reach 0.268 and 2.83, which are the highest compared with the previous results. The transmission, focusing efficiency, and numerical aperture (NA) of BOML reach 81.5%, 73.4%,
and 1.78, respectively. In addition, by improving the BOML using the design principle of Fresnel lens, a large NA of 1.9 is realized within a smaller BOML footprint of around 75 μm². Besides light focusing, we also demonstrate the beam steering capability of BOML and achieves a 7.2° tilting angle for propagation channel selection in dense PICs. Our results provide a promising solution of on-chip focusing for mode conversion and power redistribution at the micro/nanometer-scale, paving the way for dense integration of photonic systems like PICs, PNNs, and spectroscopic sensors.

2 | THEORETICAL ANALYSIS OF PHASE ENGINEERING USING BOML

In this section, the principle of phase engineering using BOML is discussed. The BOML is designed by considering the possible synergistic effect between GG-OML and GRIN-OML. The key design principle is to simultaneously optimize gradient geometry and gradient refractive index by varying the length (l) and width (w) of air slots, which are the unit cells of the all-dielectric metamaterial. Figure 1A shows the schematic diagram of the MIR BOML on an SOI wafer with a 500 nm device layer and 2 μm buried oxide, which is a common platform for MIR waveguide working in 3.6–3.8 μm wavelengths.54,60 The all-dielectric metamaterial operates at guiding modes in the propagation direction. In principle, the period (Λ) of air slots that constitute the metamaterial has a design trade-off (see Section S2 in supporting information for details). A smaller Λ allows more air slots to be embedded in a waveguide with a fixed width and increases the effective refractive difference for air slots with different widths, so as to provide a finer phase profile and larger phase difference. Meanwhile, Λ cannot be too small. Otherwise, the propagating mode will be cut off and the light cannot pass through the waveguide effectively. Considering this trade-off, we design 11 subwavelength air slots with a period (Λ) of 1.6 μm at the end of the input waveguide. The input waveguide with a width of 18 μm supports the guided wave propagation and provides collimated incidence to the metamaterial. By engineering the length and width of air slots that control the gradient geometry and gradient refractive index, respectively, the metamaterial is able to manipulate the propagation phase of the transverse electric (TE) polarized light in a controllable manner.

For light focusing, a critical criterion of OMLs is their capability of providing a large phase shift for light

![Figure 1](image-url)
passing through OMLs. The all-dielectric metamaterial needs to achieve complete phase manipulation \(2\pi\) by engineering the slot length and slot width-engineered effective index (referred to as length and effective index in the following context). In the proposed BOML, the phase shift is calculated by the phase difference between the light traveling through a metalens and the light propagating inside the waveguide. In the \(y = d\) plane perpendicular to the incident direction, the phase shift \(\Delta \phi_y\) of the plane wave after passing through a metalens can be expressed as follows:

\[
\Delta \phi_y = \left[ n_{\text{slot}} + n_{\text{Si}} \left( d - \frac{l}{2} \right) \right] k_0 - n_{\text{Si}} \left( d + \frac{l}{2} \right) k_0 = (n_{\text{slot}} - n_{\text{Si}})lk_0
\]

(1)

where \(n_{\text{slot}}\) and \(n_{\text{Si}}\) are the refractive indexes of slot and silicon, \(l\) is the slot length, and \(k_0\) is the wavenumber in a vacuum. To simplify the derivation, we denote \(\Delta n_y = n_{\text{slot}} - n_{\text{Si}}\). The phase shift can be expressed as follows:

\[
\Delta \phi_y = \Delta n_y lk_0
\]

(2)

Equation (2) shows that the phase shift induced by metamaterial can be manipulated by adjusting the effective index and length of Si slots, as indicated by the \(\Delta n_y\) term and the \(l\) term, respectively. Thanks to the guided-wave properties, the effective index is determined by the width of Si slots for different modes. To calculate the effective index, we define the filling factor \(F = w/\lambda\) and assume that the effective index of the Si-slot structure in each slot is constant. Due to the time-varying nature of the light in Si-slot structure, the effective medium theory (EMT) is used to calculate the effective index of the transverse magnetic (TM) and TE polarization in slots. With the second-order approximation considering \(\Lambda/\lambda\) term, \(44,61-63\) the effective refractive index is given as follows:

\[
\left( n_{\text{eff} - \text{TE}}^{(2)} \right)^2 = \frac{F}{n_{\text{slab} - \text{TE}}^2} + 1 - \frac{F}{\varepsilon_{g}} + \frac{1}{3} \left[ \frac{\Lambda}{\lambda} F(1 - F) \left( n_{\text{slab} - \text{TE}}^2 - 1 \right) \right] \left( 1 - \frac{k}{\varepsilon_{g}} \right)^2 \left( n_{\text{slab} - \text{TE}}^2 + 1 \right)^2
\]

(3)

\[
\left( n_{\text{eff} - \text{TM}}^{(2)} \right)^2 = F \cdot n_{\text{slab} - \text{TM}}^2 + (1 - F)\varepsilon_{g} + \frac{1}{3} \left[ \frac{\Lambda}{\lambda} F(1 - F) \left( n_{\text{slab} - \text{TE}}^2 - \varepsilon_{g} \right) \right]
\]

(4)

where \(\lambda\) is the operating wavelength, \(\varepsilon_{g} = 1\), \(n_{\text{slab} - \text{TE}}\) and \(n_{\text{slab} - \text{TM}}\) are the effective indices of the slab without the slot array, which are the analytical solutions of Equations (5) and (6)\(^{64}\):

\[
\frac{2\pi}{\lambda} \sqrt{\varepsilon_{\text{Si}}} \left[ \frac{\varepsilon_{\text{Si}} - n_{\text{slab} - \text{TE}}^2}{\varepsilon_{\text{Si}}} t - \tan^{-1} \left( \frac{n_{\text{slab} - \text{TE}}^2 - \varepsilon_{\text{Si}}}{\varepsilon_{\text{Si}} - n_{\text{slab} - \text{TE}}^2} \right) \right] = 0
\]

(5)

\[
\frac{2\pi}{\lambda} \sqrt{\varepsilon_{\text{Si}}} \left[ \frac{\varepsilon_{\text{Si}} - n_{\text{slab} - \text{TM}}^2}{\varepsilon_{\text{Si}}} t - \tan^{-1} \left( \frac{n_{\text{slab} - \text{TM}}^2 - \varepsilon_{\text{Si}}}{\varepsilon_{\text{Si}} - n_{\text{slab} - \text{TM}}^2} \right) \right] = 0
\]

(6)

where \(t\) is the thickness of the silicon layer, \(\varepsilon_{\text{Si}}\) is the effective permittivity of silicon, \(\varepsilon_{\text{SiO2}}\) is the effective permittivity of silicon dioxide (bottom cladding), and \(\varepsilon_{\text{air}}\) is the permittivity of air (up cladding). Therefore, by combining Equations (3)–(6) with appropriate numerical methods, we can get the effective index value in each slot of different widths for the fundamental mode (see Section S2 in supporting information for details). In BOML, GG-OML, and GRIN-OML, the effective index of the grid corresponding to each slot in the transverse direction can be obtained entirely. Figure 1E–G shows the grid effective index and length of the corresponding slot of BOML, GG-OML, and GRIN-OML. For TE and TM modes, the phase shift can be easily calculated by substituting the corresponding effective refractive index calculated by the second-order EMT into Equation (1).

After getting the phase shift of individual slots, we further calculate the phase gradient \(\Delta \phi_{ym}\) of the dedicated slots inside the metalens as follows:

\[
\Delta \phi_{ym} = \Delta \phi_{ym} - \Delta \phi_{yo} = (\Delta n_{ym} - \Delta n_{yo})lk_0
\]

(7)

where \(m\) is a positive integer to denote the number of slots. To simplify, we denote \(\Delta n_{ym} = \Delta n_{ym} - \Delta n_{yo}\). The phase gradient can be shown as follows:

\[
\Delta \phi_{ym} = \Delta n_{ym}lk_0
\]

(8)

We take the central slot as the reference and calculate the phase gradient of each slot using the geometric relationship as follows:
\[ \Delta \phi_{xm} = \Delta n_{xm} k_0 \left[ f - \sqrt{(m \Lambda + f^2)} \right] \]  

We treat the phase gradient as a function of focal lengths and find the first derivative of \( f \) with respect to \( \Delta \phi \):

\[ \frac{df}{d \Delta \phi_{xm}} = \frac{\sqrt{(m \Lambda + f^2)}}{\Delta n_{xm} k_0 \left( \sqrt{(m \Lambda + f^2 - f)} \right)} \]

Under the condition of \( m > 0 \), the first derivative is always negative since \( \Delta n_{xm} < 0 \), which means a larger phase gradient is required for a smaller focal length. Therefore, to achieve our goal of subwavelength focal lengths, the OML needs to be designed at a large phase gradient. From Equation (8), the phase gradient is proportional to the effective refractive index and length of the Si slot. The bigradient design combines the manipulation of gradient refractive index via width gradient and gradient geometry via length gradient, pushing the phase shift to the largest possible value. The calculated phase shift as a combined result of gradient geometry and gradient refractive index is shown in Figure 1H. This provides theoretical proof for the possibility of achieving a shorter focal length under the same or even smaller device dimension.

### 3 | DESIGN AND OPTIMIZATION OF BOML

Understanding the fundamental principle of phase engineering using BOML, we are able to design the metalens and optimize the FOMs in terms of focal length, spot size, and efficiency by engineering the length and width of slots. For light focusing, the parabolic phase is employed. The profiles of topology and index are shown in Figure 1B–D for BOML, GG-OML, and GRIN-OML designs. Since the phase profile is fixed to parabolic shape, the slot length gradient can be simply characterized by the difference between the maximum slot length and the minimum slot length in the array (\( \Delta l = l_{\text{max}} - l_{\text{min}} \)), where the length of other slots can be determined from a parabolic function. Similarly, the slot width gradient is characterized by \( \Delta w = w_{\text{max}} - w_{\text{min}} \).

For the BOML, the slot length and width gradient are symmetrically distributed. The shapes of the central slot are fixed at \( l = 1 \) \( \mu \text{m} \) and \( w = 0.4 \) \( \mu \text{m} \) to make the phase shift with high transmission, as shown in the transmission map in Figure 11. In all designs, \( l_{\text{max}} \) and \( l_{\text{min}} \) of all slots in the array will only exist in the two slots at both extreme ends, independently. Therefore, the decisive \( \Delta l \) and \( \Delta w \) are only related to \( l \) and \( w \) of the slots located at the edge of OML. After determining these two parameters, we calculate the necessary geometric parameters of the remaining eight slots using the parabolic curve distribution to mimic the phase profile of parabolic lenses. With the optimization process in Sections S3 and S4 in supporting information, \( \Delta l \) and \( \Delta w \) of the bigradient design are 9 \( \mu \text{m} \) and 0.4 \( \mu \text{m} \). In this way, we construct gradients in both the length and width of slots simultaneously, which respond to gradient geometry and gradient refractive index, respectively.

In order to evaluate the performance of BOML, GG-OML, and GRIN-OML as control devices are designed by solely implementing length gradient or width gradient (Figure 1B–D). For GG-OML, the length gradient is kept the same as BOML, and the width is 0.56 \( \mu \text{m} \) to maintain the low optical loss. A similar design principle is also for GRIN-OML, where the width gradient is kept the same as BOML, while the constant length of 4.6 \( \mu \text{m} \) makes a comparable phase gradient. To obtain an accurate design database, the dependence of phase shift and transmission on \( l \) and \( w \) for a single slot is obtained by utilizing finite-difference time-domain (FDTD) methods (Figure 1H, I). Compared with length-graded or width-graded design, the bigradient design makes full use of the steepest gradient on the phase map to obtain the most considerable phase differences for \( x \). The detailed design parameters can be found in Section S4 in supporting information. The transmission feature shows periodicity as the slot length increases and is more sensitive to variations in slot width. The optimization process of BOML is shown in Figure 1J. The lengths and widths of the 11 slots are fixed at 1 and 0.4 \( \mu \text{m} \) at the initial state. With a \( \Delta l \) increasing step of 2 \( \mu \text{m} \) and the fixed width, the focal length of the metalens will decrease continuously and then saturate when \( \Delta l \) reaches 10 \( \mu \text{m} \). Extra \( \Delta l \) only causes focusing collapse rather than further shortening of the focal length, which indicates the limitation of the length-graded method has been reached (see Section S3 in supporting information for details). Then, we fix \( \Delta l \) at 9 \( \mu \text{m} \) where the focusing effect is the best and increase \( \Delta w \) with 0.2 \( \mu \text{m} \) steps, which leads to further decrease in focal length until it approaches the physical limit (\( w \) reaches \( \Lambda \)) of the width gradient (see Section S4 in supporting information for details). The optimization process proves that the synergy of two gradients can significantly improve the focusing performance, which gives more degree of freedom compared with reported designs.

Figure 2A–C shows the 2D geometries and corresponding phase profiles of BOML, GG-OML, and GRIN-OML (see Section S4 in supporting information for details). The bigradient design obtains a steeper phase gradient, and the normalized intensity profile of \( |E_x|^2 \) at \( z \)
Figure 2: Simulation results of optimized OML. (A) Relationship between slot 2D geometries/positions and corresponding phase of BOML, (B) GG-OML, and (C) GRIN-OML. Each blue bar in the bar chart below represents the shape of the slot at the corresponding position. The red dots above represent the corresponding phases of each slot. (D) Normalized intensity profile of $|E_x|^2$ at focal plane with 3.7 μm incident MIR light following the propagation direction of $+y$ of BOML, (E) GG-OML, and (F) GRIN-OML. The white line represents the focal plane. Inset: intensity profile of $|E_x|^2$ on the focal plane. The size of the monitor represented by the white dashed frame is 6 μm × 1.5 μm. (G) The simulated spectrum of transmission, focusing efficiency, focal length, and the spot size (FWHM) of BOML, (H) GG-OML, and (I) GRIN-OML.

0.25 μm is plotted in Figure 2D–F. The center wavelength of the metalens is designed at 3.7 μm. The spot size ($s$) is defined as the full width half maximum (FWHM) of $|E_x|^2$ at the focal plane. From Figure 2D–F, BOML achieves the shortest focal length of 13.8 μm and the smallest spot size compared with the other two control devices. Although the GG-OML design also achieves a relatively small focal length and spot size, focusing is slightly deteriorative since the slot length gradient is close to the limit. The dispersions of metalenses are characterized in Figure 2G–I by several critical FOMs of three OMLs. The transmissions of the three designs are approximately consistent at around 80%, which do not show obvious dispersion characteristics. Compared with BOML and GRIN-OML, the slightly lower transmission of the GG-OML may be due to the relatively high filling factor (larger equivalent slot width) of GG-OML, which will cause an energy blocking effect at the central region of TE mode where the most mode energy concentrates. The simulation in this section briefly shows that BOML provides the dramatically small focal length and spot size in subwavelength scale with comparable transmission and efficiency as GG-OML and GRIN-OML.

4 | CHARACTERIZATION OF BOML

To verify the superiority of BOML as indicated by simulation, the OMLs are fabricated through the nanofabrication process and characterized using a quantum cascaded laser. To characterize the OMLs, we design the waveguide array to measure the light distribution before and after the focal plane. Seven parallel waveguides are arranged on the specific plane at a distance of Δy values from the origin with the waveguide width of 1.4 μm (Figure 3A). The interval of waveguides is set to 1.5 μm to prevent crosstalk (see Section S8 in supporting
information for details). The devices are fabricated using a one-mask lithography process, which means the OML is patterned together with the waveguide in the same mask and reduces the cost and complexity for integration (see Section S7 in supporting information for details). The testing setup for experiments is shown in Figure 3B (see S8 in supporting information for details). Figure 3C–E shows the SEM images of fabricated BOML, GG-

FIGURE 3 Experimental demonstration of the superiority of BOML. (A) 3D schematic view of BOML with seven output waveguides. (B) Diagram of the testing setup (see Methods). (C) SEM image of the fabricated BOML, (D) GG-OML, and (E) GRIN-OML. (F) Normalized intensity profiles of $|E_x|^2$ at $z = 0.25$ μm and testing data at different planes with different $\Delta y$ values (8, 14, 20, 30, and 40 μm) of BOML, (G) GG-OML and (H) GRIN-OML. The crosses (×) represent the measured data from the output waveguides. (I) Normalized intensity profiles of $|E_x|^2$ at $z = 0.25$ μm and testing data at different wavelengths (3.65, 3.7, 3.75, and 3.8 μm) at $\Delta y$ equal to the corresponding focal length of BOML, (J) GG-OML, and (K) GRIN-OML.
OML, and GRIN-OML. For each output waveguide, three tests are performed. The average of three test data is considered representative, and the error is acceptable (see Section S9 in supporting information for details). The characterization results show that the focal lengths in BOML, GG-OML, and GRIN-OML are 13.8, 19.5, 29.5 \( \mu m \), respectively (Figure 3F–H). It proves the superiority of BOML. In particular, for each metalens, we compare the simulated normalized \( |E_x|^2 \) profiles at \( z = 0.25 \mu m \) and testing data at different planes with different \( \Delta y \) values (8, 14, 20, 30, and 40 \( \mu m \)) of BOML with Fresnel’s design. The crosses (\( \times \)) represent the measured data from the output waveguides. (E) Normalized intensity profiles of \( |E_x|^2 \) at \( z = 0.25 \mu m \) and testing data at different wavelengths (3.65, 3.7, 3.75, and 3.8 \( \mu m \)) at \( \Delta y = 14 \mu m \) of BOML with Fresnel’s design. (F) Benchmark of \( \lambda/f \) and \( \lambda/\text{FWHM} \) of designs in this work against other designs in previous work.

**FIGURE 4** Simulation verification and experimental demonstration of BOML with Fresnel design and benchmark. (A) Relationship between slot 2D geometries/positions and corresponding phase of BOML with Fresnel’s design. A comparison between BOML with Fresnel’s design and BOML is included. (B) SEM image of the fabricated BOML with Fresnel’s design. (C) Simulated spectrum of transmission, focusing efficiency, focal length, and the spot size (FWHM) of BOML with Fresnel’s design. (D) Normalized intensity profiles of \( |E_x|^2 \) at \( z = 0.25 \mu m \) and testing data at different planes with different \( \Delta y \) values (8, 14, 20, 30, and 40 \( \mu m \)) of BOML with Fresnel’s design. The crosses (\( \times \)) represent the measured data from the output waveguides. (E) Normalized intensity profiles of \( |E_x|^2 \) at \( z = 0.25 \mu m \) and testing data at different wavelengths (3.65, 3.7, 3.75, and 3.8 \( \mu m \)) at \( \Delta y = 14 \mu m \) of BOML with Fresnel’s design. (F) Benchmark of \( \lambda/f \) and \( \lambda/\text{FWHM} \) of designs in this work against other designs in previous work.

OML, and GRIN-OML. For each output waveguide, three tests are performed. The average of three test data is considered representative, and the error is acceptable (see Section S9 in supporting information for details). The characterization results show that the focal lengths in BOML, GG-OML, and GRIN-OML are 13.8, 19.5, 29.5 \( \mu m \), respectively (Figure 3F–H). It proves the superiority of BOML. In particular, for each metalens, we compare the simulated normalized \( |E_x|^2 \) profiles at \( z = 0.25 \mu m \) (vertical waveguide center) on the focal plane under \( \Delta y = 8, 14, 20, 30, \) and \( 40 \mu m \) and signal outputs at the corresponding \( \Delta y \) position from seven output waveguides. Simulation results are consistent with experimental results and prove that all three metalenses can focus on the designed focal length, justifying the proposed design methodology. At three corresponding focal planes (\( \Delta y = 14, 20, \) and \( 30 \mu m \), respectively), we also additionally study the dispersion characteristics for the 3.65–3.8 \( \mu m \) wavelength range. Both simulations and experiments prove that the BOML, GG-OML, and GRIN-OML can all achieve low dispersion in the 3.65–3.8 \( \mu m \) wavelength range with negligible variations in focal length and spot sizes (Figure 3I–K).

**5 | FRESNEL DESIGN OF BOML**

In order to further reduce the area of the BOML, we adopt the design principle of Fresnel lens to the BOML to reduce the extra phase shift larger than \( 2\pi \). By shortening the length of slots at specific positions (\( m = \pm 4 \) and \( \pm 5 \)) to reduce the phase by \( 2k\pi \) (\( k \) is an integer), we can maintain the relative phase difference within \( 2\pi \) and decrease the area of BOML by 55.1% (Figure 4A). Figure 4B shows the SEM image of the fabricated Fresnel BOML. In the BOML with Fresnel design, the deviations of transmission, focal length, and spot size are within a reasonable range of \( \pm 10\% \) compared with standard BOML (Figure 4C). The slightly higher transmission of BOML with Fresnel design can be attributed to the shortening of slots on both sides according to the relationship between slot geometries and transmission. Due to the sudden change (shortening) of lengths of slots at specific positions, the light converging from both sides to the middle may be blocked by the longer slots inside, which will slightly increase spot size. The simulation and testing of BOML with Fresnel design also demonstrate its ability to achieve efficient in-plane focusing and low dispersion characteristics (Figure 4D,E).
For the designed OML, an asymmetrical phase gradient can be achieved by reconstructing the slot array with an asymmetrical length and width gradient. Then, the offset of the focal point relative to the centerline can be consequently realized. For beam steerers, two output waveguides are designed along the central axis with $\Delta y$ fixed at $20 \mu m$ to translate the steering angle to the power ratio of two channels (Figure 5D). For the verification of the beam steering effect, we introduce the following variables and definitions for characterization. According to slot number $m$, the slots in the array are divided into two groups. The positive $m$ group contains five slots with $m \geq 0$, and the negative $m$ group contains five slots with $m \leq 0$ (Figure 5E). $L$ and $W$ are defined as $\Delta l_{(m \geq 0)} - \Delta l_{(m \leq 0)}$ and $\Delta w_{(m \geq 0)} - \Delta w_{(m \leq 0)}$ to describe the difference in slot length gradient and slot width gradient, which produces the asymmetric phase gradient to trigger the beam steering effect. In the positive $m$ group, $\Delta l_{(m \geq 0)}$ and $\Delta w_{(m \geq 0)}$ will only exist in the $m = 5$ slot simultaneously. Moreover, in the negative $p$ group, $\Delta l_{(m \leq 0)}$ and $\Delta w_{(m \leq 0)}$ will only exist in the $m = -5$ slot simultaneously. By determining the length and width of the two slots with $m = \pm 5$, we generate the parameters of other slots with the asymmetric gradient by adding a linear function on parabolic distribution. We then design a process of beam steering with two subprocesses. In the first subprocess, $L$ is firstly decreased from 0 to $-5 \mu m$. And then, $W$ is decreased from 0 to $-0.4 \mu m$, which is overlaid on the existing $L$. The phase in this process is defined as the negative asymmetric phase (NAP). In the second subprocess oppositely, $L$ is firstly increased from 0 to $5 \mu m$. And then, $W$ is increased from 0 to $0.4 \mu m$, which is overlaid on the existing $L$. The phase in this process is defined as the positive asymmetric phase (PAP). Presented by the colormap in Figure 5E, the deflection of the focused light can be observed as the difference in the output signal intensity at various states in the entire process. A larger phase gradient on one side (NAP and PAP) is supposed to cause the light to be more violently deflected to the opposite side, thereby causing the focused beam to deflect to the opposite side with an overall beam scanning angle of $\pm 3.6^\circ$. The deflected light is captured by the matched waveguide and revealed by the increase of signal intensity. Five states in the continuous increasing process of PAP (see Section S6 in supporting information for details) are extracted to plot the distribution of normalized $E_x$ at $z = 0.25 \mu m$, which visually shows the relationship between beam deflection and slot geometric gradient (Figure 5F). For experimental demonstration, we fabricate 10 samples with various states in the increasing process of PAP (see Section S6 in supporting information for details). The corresponding 10 normalized intensity profiles of $|E_x|^2$ (at $z = 0.25 \mu m$ and $y = 20 \mu m$) given by
numerical simulation are plotted in Figure 5G. The peaks of the profiles continuously deflect to the direction of $x < 0$ with the increase of PAP caused by the change in slot geometries. The measured signal intensities of two output waveguides agree well with simulated profiles, which can strongly prove that the beam has achieved the in-plane deflection. The power splitting ratio at each beam steering angle is presented as the inset figure of Figure 5G, indicating the maximum power splitting occurs at 3.32\(^\circ\).

The implementation of BOML-based on-chip mode conversion and beam steering provides a new degree of freedom for on-chip light manipulation in a compact footprint with the aid of subwavelength structures. Although the complementary metal-oxide-semiconductor (CMOS) process has been developed to 3 nm node, dense photonic integration is still challenging due to the lack of compact components to manipulate light on-chip. Our BOML provides a global design methodology for on-chip focusing from visible to infrared with the scaling of the device scale. Additionally, the BOML achieved by the slot metamaterials can be applied to waveguides based on other dielectric materials, such as SiN, Ge, AlN, etc. Furthermore, our work also provides a new pathway for possible

FIGURE 5 Results of metalens-assisted mode converters and on-chip beam steering. (A) SEM image of fabricated BOML-assisted mode converter. (B) Comparison of mode conversion effect by the distribution of normalized $E_x$ at $z = 0.25$ μm of BOML-assisted mode converter and traditional tapered mode converter. The effective length for mode conversion is 14 μm. (C) Measured conversion efficiency spectrum of metalens-assisted mode converter with BOML, BOML with Fresnel design, GG-OML, and GRIN-OML integrated. Inset: SEM images of corresponding fabricated metalens-assisted mode converter. (D) SEM image of the fabricated beam steerer with $L$ of 5 μm and $W$ of 0.4 μm. (E) Simulated colormap of the change in signal intensity from output waveguides with different states of negative asymmetric phase (NAP) and positive asymmetric phase (PAP). The intensity data for colormap plotting indicate the normalized intensity of $|E_0|^2$ at $z = 0.25$ μm. The vertical axis indicates the beam steering angles. (F) Distribution of normalized $E_x$ at $z = 0.25$ μm of five different states in the increasing process of PAP. (G) Normalized intensity profiles of $|E_0|^2$ at $z = 0.25$ μm and testing data of 10 different states in the increasing process of PAP. The corresponding power splitting ratios at each beam steering angle are presented as an inset figure.
applications of light power arrangement for guided-wave devices in the confined area. With feasible tuning methods, it is possible to achieve dynamic modulation by filling the slot with other materials with switchable optical properties such as nano-opto-electro-mechanical systems,72–75 Pockels materials,7,76,77 and phase change materials.13,78

7 | CONCLUSIONS

In this paper, we design a bigradient OML by combining two degrees of freedom in terms of gradient geometry and gradient refractive index. By doing so, BMOL overcomes the limitation of phase gradient using GG-OML and GRIN-OML and produces a more significant phase gradient for the on-chip light focusing, resulting in ultrasmall focal lengths and spot sizes at the subwavelength scale. Characterized by a MIR quantum cascaded laser (QCL), the BOML presents superior in-plane focusing and robust dispersion characteristics, which have the best FOMs of $\lambda/f$, $\lambda/FWHM$, and NA (0.268, 2.83, and 1.78) compared with published results. Harnessing the Fresnel lens design, the above FOMs can be maintained at 0.294, 2.69, and 1.9, even if the footprint of BOML is compressed by 55.1%. The spot sizes reach the subwavelength scale and match with single-mode waveguides at a 3.7 $\mu$m wavelength. Furthermore, with customized phase profiles, BOML-assisted compact mode converters and beam steerers are demonstrated to focus and tilt light from multimode to single-mode waveguides in subwavelength scale with an efficiency of 80% and steering range of 7.2°. In conclusion, the proposed BOML could be a multifunctional component in a compact footprint for dense PICs integration, enabling applications such as all-optical PNNs, complex photonic communication, and integrated spectroscopic sensors.

8 | EXPERIMENTAL SECTION

8.1 | Numerical simulation

A three-dimensional finite-difference-time-domain method (http://www.lumerical.com/tcad-products/fdtd/) is used to numerically simulate field distribution, transmission, and other effective parameters of the metalenses. The conformal mesh with a spatial resolution less than 1/20 of the smallest feature size is applied in all simulations. Transmission of the OML is obtained with a monitor placed at the upper edge of the metalenses. Focusing efficiency is defined as the ratio of light passing through a rectangular area with a width equal to three times the FWHM (1.5 $\mu$m height) on the focal plane and the light passing through the metalens.

8.2 | Device fabrication

The fabrication process starts from a commercially available 8-inch SOI wafer (Soitec) with a 0.5 $\mu$m Si device layer and 2 $\mu$m SiO2 BOX layer. After dicing to 1 $\times$ 1 cm2 chip and sonication cleaning, ZEP resists then spin-coated on the surface treated with O2 plasma by 2000 rpm with prebaking at 200°C for 2 min. The slots and waveguide structures are patterned by electron beam lithography (EBL, JEOL FS6300). Inductively coupled plasma (ICP, Oxford Instruments) etching is used to perform a full etch of the structures with customized recipes. The fabricated device can be obtained after removing the residual ZEP resists and performing the necessary cleaning process using acetone, IPA, and DI water. A diagram of the process flow is shown in Section S7 in supporting information.

8.3 | Device measurement

Light is emitted from the MIR QCL (Daylight Solution MIRCat). A half-wave plate (Thorlabs) is used to control the polarization state and ensure TE mode is excited about the experiment. The light is then modulated by a mechanical chopper, which serves as an external reference signal to the lock-in amplifier (Stanford Research System) to reduce noise. The light is then calibrated to the ZrF4 MIR fiber (Thorlabs) through a lens and coupled to the device sitting on the 6-axis sample stage (Kohzu). The output light by another MIR fiber and routed to the MIR amplified detector (Thorlabs) and finally coupled to the lock-in amplifier for processing. The LabView software is used to optimize parameters and obtain data.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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