

AN OPTICAL UNIT AND METHOD FOR COLLIMATING, FOCUSING OR EXPANDING LIGHT BEAM

TECHNICAL FIELD

[0001] The present disclosure generally relates to an optical unit and a method for collimating, focusing or expanding light beam.

BACKGROUND

[0002] The optical components working in the mid-infrared (IR) range are increasingly important as the mid-IR range holds the fingerprint signatures of many substances that are crucial for medical technology and gas sensing application. Chip-scale photonic elements, which are indispensable for compact and robust sensing/spectroscopic applications, need an equally compact light delivery to the off-chip detectors. Unfortunately, the detectors in the mid-IR range usually rely on gas immersion to perform detecting function, resulting in an unavoidable blockage of millimeter scale between the chip and the active area of the detector.

[0003] Therefore, there exists a need to provide a compact and robust solution to direct light off photonic chips to detectors in the mid-IR range.

SUMMARY

[0004] According to a first aspect of the present disclosure, an optical unit is provided. The optical unit may include: a waveguide component; and a collimating metalens optically coupled to the waveguide component and configured to collimate, focus or expand light beam transmitted by the waveguide component on to a detection plane, wherein the collimating metalens includes a metasurface having nanostructures extending toward the detection plane.

[0005] According to a second aspect of the present disclosure, a method for collimating, focusing or expanding light beam is provided. The method includes: transmitting light beam by a waveguide component; receiving the light beam from the waveguide component by a collimating metalens optically coupled to the waveguide; and collimating, focusing or expanding, by the collimating metalens, the light beam received on to a detection plane, wherein the collimating metalens includes a metasurface having nanostructures extending toward the detection plane.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. 1 is a block diagram depicting an optical unit according to various embodiments of the present disclosure.

[0007] FIG. 2A and FIG. 2B are block diagrams depicting the optical unit of FIG. 1 according to various embodiments of the present disclosure.

[0008] FIG. 3 is a block diagram depicting an optical unit according to various embodiments of the present disclosure.

[0009] FIG. 4 is a flowchart showing a method for designing an optical unit according to various embodiments of the present disclosure.

[0010] FIG. 5 shows scanning electron microscope images of a metalens of an optical unit, according to various embodiments of the present disclosure.

[0011] FIG. 6A shows the far field projection of the output beam from a waveguide component of an optical unit, according to various embodiments of the present disclosure; and FIG. 6B shows the far field projection of the output beam from a metalens of an optical unit, according to various embodiments of the present disclosure.

[0012] FIGS. 7A and 7B show a 1-dimensional array of optical units and a 2-dimensional array of optical units, respectively, according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

[0013] Embodiments described below in the context of a device, apparatus, or system are analogously valid for the respective methods, and vice versa. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment, and a part of one implementation may be combined with a part of another implementation.

[0014] It should be understood that the singular terms "a", "an", and "the" include plural references unless context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise.

[0015] It will be further understood that the terms "comprise" (and any form of comprise, such as "comprises" and "comprising"), "have" (and any form of have, such as "has" and "having"), "include" (and any form of include, such as "includes" and "including"), and "contain" (and any form of contain, such as "contains" and "containing") are open-ended linking verbs. As a result, a method or device that "comprises," "has," "includes" or "contains" one or more steps or elements possesses those one or more steps or elements, but is not limited

to possessing only those one or more steps or elements. Likewise, a step of a method or an element of a device that “comprises,” “has,” “includes” or “contains” one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

[00016] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about,” “substantially”, is not limited to the precise value specified but within tolerances that are acceptable for operation of the embodiment for an application for which it is intended. In some instances, the approximating language may correspond to the precision of an instrument for measuring the value.

[00017] Several approaches may be utilized towards a compact and robust solution to direct light off a photonic chip in the mid-IR range, including: using an output coupler with small beam divergence or incorporating an additional collimator after the on-chip coupler. Although grating coupler (GC) may be designed to have small divergence angle, it's generally infeasible to overcome millimeter distance without having to lose a significant amount of the power. Even worse, a GC of a general design may usually achieve 50% emission efficiency at the best, owing to the symmetry of emission. An edge coupler (EC) may be an alternative choice of coupler that is able to achieve 100% efficiency, i.e. to direct 100% of the input light into a single direction. The downside of the EC may be that the beam divergence is too big to be used in any practical configuration.

[00018] A collimating lens – sometimes even the focusing version of it – may perform excellently in light beam manipulation, with only minor compromise on the power efficiency if the right material is found. Metalens – a product of phase engineering based on nanostructure arrays – is flat and compact. It is able to reduce the size of the device while imposing little challenges on the assembly since unlike conventional lenses there are no curved surfaces. Moreover, it is the flat and square shape of the metalens that gives chance to improving the refractive index of the environment into which on-chip coupler output the beam, effectively reducing the beam divergence. On the other hand, an array of metalens can be patterned on a single chip to accommodate different coupling conditions of various optical channels, which prove essential in keeping the small size of multi-channeled applications. By packaging

together an EC and a customized metalens, a compact and power efficient output coupler for the mid-IR regime can be made possible.

[00019] Various aspects of what is described here seek to provide an optical unit, for example, the optical unit may include a waveguide component (e.g. an edge coupler), and a collimating metalens optically coupled to the waveguide component and configured to collimate, focus or expand light beam transmitted by the waveguide component on to a detection plane. The collimating metalens may include a metasurface having nanostructures extending toward the detection plane. The proposed integrated assembly may achieve overall 58.6% power efficiency at a mid-infrared (IR) wavelength of 6 μm . The waveguide component of the proposed optical unit may provide advantageously compact and robust solution to direct light off a photonic chip in the mid-IR range. Further, the use of metalens may keep the size of the optical unit small while significantly increasing its working distance. Both the waveguide component and the metalens may be fabricated by CMOS-compatible Ge-on-Si platform, so the integrated assembly may be mass-produced at an inexpensive price and prove to be useful to all chip-scale mid-IR applications including spectroscopy, hyperspectral imaging and sensing.

[00020] In various aspects, the waveguide may be arranged in contact with the metalens or spaced apart by a small gap (e.g. 0.5 μm) in a manner that the output beam from the waveguide component may continue traveling as guided wave and incident on the substrate of the metalens, i.e. output into a high-index medium of the substrate. That is, the light beam may travel from the waveguide component, to the substrate of the metalens and to the metasurface of the metalens. In other words, the light beam may be diverged by the waveguide component into a plurality of sub-beams (e.g. two sub-beams), the plurality of sub-beams may be further diverged by propagating through the substrate of the metalens, and the plurality of further diverged sub-beams may be phase-compensated by propagating through the metasurface of the metalens into collimated, focused, or expanded light beam.

[00021] In some aspects, for mid-IR application, the waveguide component and the metasurface of the metalens may be made of a transparent material, for example, Ge. The substrate of the metalens may be made of, for example, Si. For the near infrared range application, the waveguide component may be made of Si/SiN/other transparent materials, and the metalens may be made of Si/SiN pillars on Si/glass substrate. That is, the materials for the waveguide and the metalens may be selected according to application requirements so as to provide an improved coupling efficiency therebetween.

[00022] The following examples pertain to various aspects of the present disclosure.

[00023] Example 1 is an optical unit, including: a waveguide component; and a collimating metalens optically coupled to the waveguide component and configured to collimate, focus or expand light beam transmitted by the waveguide component on to a detection plane, wherein the collimating metalens includes a metasurface having nanostructures extending toward the detection plane.

[00024] In Example 2, the subject matter of Example 1 may optionally include that the waveguide component includes a tapered waveguide or a straight waveguide.

[00025] In Example 3, the subject matter of Example 1 may optionally include that the waveguide component is an edge-coupler optically coupled to a photonic chip.

[00026] In Example 4, the subject matter of Example 1 may optionally include that the collimating metalens is arranged in a direction non-parallel to transmission directions of the light beam transmitted by the waveguide component.

[00027] In Example 5, the subject matter of Example 1 may optionally include that the collimating metalens includes a substrate having a first surface and an opposing second surface, wherein the first surface of the substrate faces the waveguide and the second surface is the metasurface having the nanostructures extending toward the detection plane.

[00028] In Example 6, the subject matter of Example 5 may optionally include that the first surface of the substrate of the collimating metalens is in contact with an output end of the waveguide component in a manner that the light beam transmitted by the waveguide component are incident on the first surface of the substrate of the collimating metalens.

[00029] In Example 7, the subject matter of Example 5 may optionally include that the first surface of the substrate of the collimating metalens is spaced apart from an output end of the waveguide component in a manner that the light beam transmitted by the waveguide component are incident on the first surface of the substrate of the collimating metalens.

[00030] In Example 8, the subject matter of Example 6 or Example 7 may optionally include that the metasurface of the collimating metalens is parallel with a facet of the output end of the waveguide component.

[00031] In Example 9, the subject matter of Example 6 or Example 7 may optionally include that the light beam transmitted by the waveguide component include sub-beams, and the sub-beams are incident on the first surface at different oblique incident angles.

[00032] In Example 10, the subject matter of Example 7 may optionally include that the first surface of the substrate of the collimating metalens is spaced apart from the output end of the waveguide component by a distance of 0.5 μ m.

[00033] In Example 11, the subject matter of Example 1 may optionally include that the nanostructures include cylindrical-shaped, square-shaped, triangular-shaped, rectangular-shaped, hexagonal-shaped pillars having a height between 0.4 and 4 μ m, and a lateral size that varies between 0.1 and 2 μ m.

[00034] In Example 12, the subject matter of Example 1 may optionally include that the nanostructures are separated from nearest neighbor nanostructures by a gap of at least 60nm.

[00035] In Example 13, the subject matter of Example 1 may optionally include that the nanostructures include a plurality of nanopillars of different diameters corresponding to different phase changes of the light beam transmitted by the waveguide component so as to collimate, focus or expand the light beam transmitted by the waveguide component on to the detection plane.

[00036] In Example 14, the subject matter of Example 1 may optionally include that the nanostructures include a plurality of nanopillars having negative sidewall angles with a top radius greater than a bottom radius of the plurality of nanopillars.

[00037] In Example 15, the subject matter of Example 1 may optionally include that an optical detector is provided at the detection plane to detect the collimated, focused or expanded light beam by the collimating metalens.

[00038] In Example 16, the subject matter of Example 1 may optionally include that the optical detector includes a gas or vacuum chamber provided between the collimating metalens and the optical detector.

[00039] In Example 17, the subject matter of Example 1 may optionally include that the waveguide component and the nanostructures of the collimating metalens are made of a same material selected from Germanium (Ge), Si, SixOy, SixNy, and/or TiO₂.

[00040] In Example 18, the subject matter of Example 1 may optionally include that the substrate of the collimating metalens is made of a transparent material and a thickness of the substrate ranges from 500 μ m to 1mm.

[00041] In Example 19, the subject matter of Example 1 may optionally include that the light beam transmitted by the waveguide component have a wavelength ranging from infrared to visible light.

[00042] Example 20 is a method for collimating, focusing or expanding light beam, the method including: transmitting light beam by a waveguide component; receiving the light beam from the waveguide component by a collimating metalens optically coupled to the waveguide; and collimating, focusing or expanding, by the collimating metalens, the light beam received on to a detection plane, wherein the collimating metalens includes a metasurface having nanostructures extending toward the detection plane.

[00043] In the following description, example configurations and systems/devices are first described that may employ the techniques described herein. Example details and methods are then described which may be performed in the example configurations and by the systems/devices as well as in other configurations and by other systems/devices. Consequently, implementation of the example details and methods is not limited to the example configurations and systems/devices, and the example configurations and systems/devices are not limited to the example details and methods.

[00044] FIG. 1 is a block diagram depicting an optical unit 100 according to various embodiments of the present disclosure. FIG. 2A and FIG. 2B are block diagrams depicting the top view and side view of the optical unit 100, respectively, according to various embodiments of the present disclosure. FIG. 1 also shows a frame of reference 101 having three orthogonal axes. The frame of reference 101 includes a first axis in a first direction (e.g., the X-direction), a second axis in a second direction (e.g., the Y-direction), and a third axis in a third direction (e.g., the Z-direction). The first, second, and third directions are perpendicular to each other.

[00045] According to various non-limiting embodiments, the optical unit 100 may include a waveguide component 110 and a collimating metalens 120 optically coupled to the waveguide component 110. The collimating metalens 120 may be configured to collimate, focus or expand light beam (e.g. 201 as shown in FIGS. 2A and 2B) transmitted by the waveguide component 110 on to a detection plane 130. The collimating metalens 120 may include a metasurface 122 having nanostructures extending toward the detection plane 130. The light beam transmitted by the waveguide component 110 may have a wavelength ranging from infrared to visible light.

[00046] In the context of **various embodiments**, “**optically coupled**” may refer to being capable of transferring, transmitting, or propagating optical signals (i.e. light beam) between two elements through a direct connection or a connection through one or more intermediary elements. **As used herein, the term “coupled” herein may be understood that both direct coupling or indirect coupling (in other words: coupling without direct contact) may be**

provided. Accordingly, the collimating metalens 120 optically coupled to the waveguide component 110 may include the collimating metalens 120 in direct contact with the waveguide component 110 and the collimating metalens 120 spaced apart (e.g. by an intermediary element, for example, air) from the waveguide component 110, and in any event, optical signals may be transferred, transmitted or propagating between the collimating metalens 120 and the waveguide component 110.

[00047] In the context of various embodiments, a “waveguide component” may refer to a waveguide that may confine one or more optical modes in at least two dimensions, e.g., in the transverse directions (x- and y- directions) such that the mode is guided and propagates along a longitudinal axis of the waveguide, e.g., along the z-direction (direction of propagation of the light beam). As a non-limiting example, a waveguide may include a planar surface defined along the width (W) direction (e.g., x-direction) and/or the height (H) direction (e.g., y-direction) of the waveguide. The waveguide component 100 may be arranged parallel to the X-Z plane extending from a point in the negative z-direction and to zero in the Z-direction (i.e. $z=0$).

[00048] According to various non-limiting embodiments, the waveguide component 110 may include a tapered waveguide (as shown in FIGS. 1, 2A and 2B, with a narrow input end and a wide output end) or a straight waveguide (not shown). According to various non-limiting embodiments, the waveguide component 110 may be an edge-coupler or a part of an edge-coupler optically coupled to a photonic chip 140.

[00049] According to various non-limiting embodiments, the collimating metalens 120 may be arranged in a direction (e.g. along the Y-direction) non-parallel (e.g. perpendicular) to transmission/propagation directions (e.g. in the X-Z plane) of the light beam transmitted by the waveguide component 110. In other words, the collimating metalens 120 may be arranged in a plane (e.g. the X-Y plane) non-parallel (e.g. perpendicular) to another plane (e.g. the X-Z plane) where the waveguide component 110 is arranged.

[00050] According to various non-limiting embodiments, the collimating metalens 120 may include a substrate 124 having a first surface 124a and an opposing second surface 124b. The first surface 124a of the substrate 124 may face the waveguide 110 and the second surface 124b may form the metasurface 122 having the nanostructures extending toward the detection plane 130.

[00051] In some embodiments, the first surface 124a of the substrate 124 of the collimating metalens 120 may be in contact with an output end 110a of the waveguide component 110 in

a manner that the light beam 201 transmitted by the waveguide component 110 are incident on the first surface 124a of the substrate 124 of the collimating metalens 120. In other words, the metalens 120 may be arranged such that the first surface 124a of the substrate 124 is in the X-Y plane ($z=0$).

[00052] In other embodiments, the first surface 124a of the substrate 124 of the collimating metalens 120 may be spaced apart from an output end 110a (FIG. 2A and FIG. 2B) of the waveguide component 110 in a manner that the light beam 201 transmitted by the waveguide component 110 are incident on the first surface 124a of the substrate 124 of the collimating metalens 120. The light beam 201 transmitted by the waveguide component 110 may be split into two sub-beams due to the gap (e.g. less than $10\mu\text{m}$) between the metalens 120 and the waveguide component 110, and the two sub-beams may be incident with different oblique angles on the first surface 124a of the substrate 124 of the collimating metalens 120. The two sub-beams may be collimated (e.g. phase-compensation) by the metalens 120 into one light beam. In some embodiments, the first surface 124a of the substrate 124 of the collimating metalens 120 may be spaced apart from the output end 110a of the waveguide component 110 by a distance of $0.5\mu\text{m}$.

[00053] According to various non-limiting embodiments, the metasurface 122 of the collimating metalens 120 may be parallel with a facet of the output end 110a of the waveguide component 110. For example, in the context of the first surface 124a of the substrate 124 of the collimating metalens 120 in contact with the output end 110a of the waveguide component 110, the metasurface 122 may be parallel to a contact facet of the output end 110a; in the context of the first surface 124a of the substrate 124 of the collimating metalens 120 spaced apart from the output end 110a of the waveguide component 110, the metasurface 122 may be parallel to a facet of the output end 110a facing the first surface 124a.

[00054] As shown in FIGS. 2A and 2B, the light beam 201 may be transmitted by the waveguide component 110 and separated into sub-beams (e.g. each sub-beam has a transmission direction in the X-Z plane). In other words, the light beam 201 transmitted by the waveguide component 110 may include sub-beams, and the sub-beams may be incident on the first surface 124a at different oblique incident angles.

[00055] According to various non-limiting embodiments, the optical unit 100 may further include an optical detector 131 provided at the detection plane 130 to detect the collimated, focused or expanded light beam 203 by the collimating metalens 120. The optical detector 131

may include a gas or vacuum chamber 132 provided between the collimating metalens 122 and the optical detector 131.

[00056] According to various non-limiting embodiments, the waveguide component 110 and the nanostructures of the collimating metalens 120 may be made of a same material selected from Germanium (Ge), Si, Si_xO_y , Si_xN_y , and/or TiO_2 .

[00057] According to various non-limiting embodiments, the substrate 124 of the collimating metalens 120 may be made of a transparent material. A thickness of the substrate 124 may range from 500 μm to 1mm, particularly 750 μm .

[00058] According to various non-limiting embodiments, the nanostructures may include cylindrical-shaped, square-shaped, triangular-shaped, rectangular-shaped, hexagonal-shaped nanopillars. The nanopillars may include a height between 0.4 and 4 μm , particularly 2 μm , and a lateral size that varies between 0.1 and 2 μm , particularly, 0.3 to 2 μm . The nanostructures may be separated from nearest neighbor nanostructures by a gap (g) of at least 60nm. In some embodiments, the nanostructures may include a plurality of nanopillars of different diameters corresponding to different phase changes of the light beam transmitted by the waveguide component 110 so as to collimate, focus or expand the light beam transmitted by the waveguide component 110 on to the detection plane 130. The different diameters of the nanopillars may be determined as described herein with reference to FIG. 4. In some embodiments, the nanostructures may include a plurality of nanopillars having negative sidewall angles with a top radius greater than a bottom radius of the plurality of nanopillars. In other embodiments, the nanostructures may include a plurality of nanopillars having straight sidewalls. Further details of the nanostructures will be described with reference to FIG. 5. Improved metalens designs may provide lower loss, improved Strehl ratio for on-axis focusing metalens and improved beam quality for off-axis focusing metalens. Advantageously, the metalens with an improved nanostructure profile as described herein may provide improved beam quality at focus point, i.e. less scattered light beam outside the focal point.

[00059] FIG. 3 is a block diagram depicting an optical unit 300 according to various embodiments of the present disclosure. The optical unit 300 may be similar to the optical unit 100 of FIG. 1 and include the features of the optical unit 100, and thus various embodiments, modifications and variations described with reference to the optical unit 100 of FIG. 1 are analogously valid for the optical unit 300 of FIG. 3, and vice versa.

[00060] According to various non-limiting embodiments, the optical unit 300 may include a waveguide component 310 and a collimating metalens optically coupled to the waveguide

component 310. The collimating metalens may be configured to collimate, focus or expand light beam (e.g. 301 as shown in FIG. 3) transmitted by the waveguide component 310 on to a detection plane 330. The collimating metalens may include a metasurface 322 having nanostructures extending toward the detection plane 130. The collimating metalens may further include a substrate 324.

[00061] According to various non-limiting embodiments, the waveguide component 310 may be an edge-coupler optically coupled to a photonic chip 340. The photonic chip 340 may include a step 342. The substrate 324 of the collimating metalens may be arranged on the step 342, for example, secured by a thin layer of epoxy 30. The waveguide component 310 may have an output end aligning with a wall (i.e. in the Y-direction) of the step 342. A first surface of the substrate 324 may be in contact with the output end of the waveguide component 310 and the wall of the step 324 of the photonic chip 340; and a second surface of the substrate 324 may form a metasurface parallel to the output end of the waveguide component 310 and the wall of the step 324 of the photonic chip 340. The metasurface may be arranged in alignment with transmission direction of the waveguide component 310 as so to collimating, focusing or expanding the light beam transmitted by the waveguide component 310. The collimated, focused or expanded beam 303 may be detected by a detector 331 at the detection plane 330.

[00062] FIG. 4 is a flowchart showing a method 400 for designing an optical unit (e.g. the optical unit 100, 300) according to various embodiments of the present disclosure.

[00063] At step 401, set up a metasurface library (e.g. Ge nanopillars with different diameters). The metasurface library includes arrays of nanopillars with a fixed pitch Λ and a smallest inter-nanopillar gap size g . Upper bound of transmission efficiency may be determined by the smallest inter-nanopillar gap size. In other words, the smaller the gap, the higher the coupling efficiency likely to be achieved. When the pitch and smallest pillar diameter is set, the smallest gap size may be correspondingly determined to get the full range of allowable pillar sizes to constitute the metasurface library. Such specification may also address the limiting requirement for fabrication, which is a critical design parameter that may be pre-defined.

[00064] At step 403, determine if the metasurface library covers phase changes (e.g. $0-2\pi$) and the transmission efficiencies of the arrays are above a predetermined threshold (e.g. 30%). If yes, proceed to step 405. If no, go back to step 401 to continue setting up the metasurface library by optimizing the fixed pitch Λ and the smallest inter-nanopillar gap size g .

[00065] At step 405, pixelate the metalens in the XY-plane and calculate the corresponding phase profile $\Psi(x, y)$ of the light beam when the light beam has propagated through the waveguide and the substrate, thereby reaching the second surface of the substrate where the metasurface is formed. The calculation steps may include: 1. Calculate the light beam at the exit end of the waveguide; 2. Calculate beam propagation of the light beam before it hits the metasurface; 3. Build metasurface according to the phase profile of the propagated beam. If there is an air gap between the waveguide output facet (where there is no cladding around the waveguide) and the metalens substrate, the beam may be split into two sub-beams; subsequent propagation may treat the two sub-beams as a whole and calculate both together.

[00066] At step 407, select a metasurface from the metasurface library to be placed in each pixel of the metalens across the XY-plane so that the corresponding phase change of the selected metasurface cancels out the phase profile $\Psi(x, y)$ calculated in step 405, resulting in an all-zero phase wavefront. That is, the metalens (i.e. the metasurface) may be so designed that phase changes of the light beam caused by the metalens cancel out the phase profiles $\Psi(x, y)$ of the light beam when the light beam has propagated through the waveguide and the substrate. In doing so, an all-zero wave front may be obtained and the diverging beam output from the waveguide component and the substrate of the metalens may be transformed into a collimated plane wave. Further, as the metalens may be pixelated and each pixel of the metalens may include arrays of nanopillars with different diameters, thereby each pixel of the metalens (i.e. metasurface) provides a different phase change for the light beam (i.e. for each sub-beam of the light beam).

[00067] At step 409, design the metalens according to step 407 and test the metalens performance by numerical simulations.

[00068] While the method described above is illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

[00069] FIG. 5 shows scanning electron microscope (SEM) images of a metalens of an optical unit, according to various embodiments of the present disclosure. The top view of the

FIG. 5 shows the SEM image of the metalens, the middle inset shows a section of the metalens and the bottom inset shows an enlarged portion of the section as shown in the middle inset. As shown in the middle and bottom insets of FIG. 5, the metalens may include a plurality (e.g. thousands) of nanopillars with different diameters, the different diameters corresponding to different phase response to the light beam (i.e. different sub-beams of the light beam). Accordingly, when put together, the optical unit may provide an intended phase profile that bends a diverging beam into a collimated beam.

[00070] According to various non-limiting embodiments, the nanopillars may have a height between 0.4 and 4 μm , particularly 2 μm , and a lateral size (e.g. diameter) that varies between 0.1 and 2 μm , particularly, 0.3 to 2 μm . The lower bound (e.g. 300 nm) of the lateral size may be so selected that nanopillars with diameters of the lower bound remain standing, i.e. not falling, thereby providing improved performance. There may be a one-to-one correspondence between pillars of different diameters (height is fixed) and the relative phase created by light transmitted through the pillars. The relative phase may increase monotonically with the pillar diameters. To find an optimum set of pillar diameters as an efficient library for the metalens, firstly set the smallest diameter as the smallest achievable pillar by fabrication; then, with the smallest achievable gap size determined, find the pitch size that guarantees at least 2π relative phase change for the maximum allowable pillar diameter; the upper and lower bound of the pillar diameter may be determined and the library may take any discrete value within the range.

[00071] Finite-difference time-domain (FDTD) method may be used to simulate an optical unit (e.g. the optical unit 100, 300) and, correspondingly, numerically study the power efficiency of the optical unit. The optical unit may include a waveguide component (e.g. the waveguide component 110, 310) and a collimating metalens (e.g. the collimating metalens 120, 320) optically coupled to the waveguide component. The collimating metalens may be configured to collimate, focus or expand light beam (e.g. 201 as shown in FIGS. 2A and 2B, 301 as shown in FIG. 3) transmitted by the waveguide component on to a detection plane (e.g. the detection plane 130, 330). The collimating metalens may include a metasurface (e.g. the metasurface 122, 322) having nanostructures extending toward the detection plane. The waveguide component may be a tapered waveguide having an input end and an output end (e.g. the output end 110a). The widths (e.g. along the X-direction) at the input and output ends of the tapered waveguide are set as 1.9 μm and 12 μm , respectively, for FDTD simulation. The FDTD simulation shows that the propagation loss along the tapered waveguide is 0.5%, which may be taken as negligible. No propagation loss may be expected for a straight waveguide for

a short propagation distance. FIG. 6A and FIG. 6B show the simulation results of the far field projection of the optical unit.

[00072] FIG. 6A shows the far field projection of an output beam from the waveguide component (e.g. the waveguide component 110, 310) of the optical unit (e.g. the optical unit 100, 300), according to various embodiments of the present disclosure; and FIG. 6B shows the far field projection of an output beam from a metalens (e.g. the metalens 120, 320) of an optical unit (e.g. the optical unit 100, 300), according to various embodiments of the present disclosure.

[00073] As show in FIG. 6A and FIG. 6B, the x-axis (ux) represents $\sin(\theta)\cos(\phi)$ and the y-axis (uy) represents $\sin(\theta)\sin(\phi)$, where θ and ϕ denotes the polar and azimuthal angle, respectively, in the spherical coordinates.

[00074] The light beam may have a divergence (e.g. 14.4° in simulation with the above parameters) in the X-direction after propagating through the waveguide component, which gives rise to an increase (e.g. around $400\text{ }\mu\text{m}$ in simulation with the above parameters) on the beam waist. The metalens may be therefore set to have a sufficient span in the X-direction (e.g. $700\text{ }\mu\text{m}$ in simulation with the above parameters) to cover (most of) the light beam transmitted by the waveguide component. The metalens may be also set to have a sufficient span in Y-direction (e.g. $250\text{ }\mu\text{m}$ in simulation with the above parameters) corresponding to the beam divergence in this direction (e.g. 5° in simulation with the above parameters). In other words, a respective span of the metalens (e.g. diameter, size, length/width of the metalens) in a respective direction may be determined based on the beam divergence by the waveguide component in the respective direction so as to receive the light beam transmitted by the waveguide component. Stated differently, a respective span of the metalens (e.g. diameter, size, length/width of the metalens) in a respective direction may be greater than or equal to the beam divergence by the waveguide component in the respective direction so as to receive the light beam transmitted by the waveguide component.

[00075] The light beam transmitted by the waveguide component may further travel a distance being a thickness of a substrate (e.g. the substrate 124, 324) of the metalens (e.g. $750\text{ }\mu\text{m}$ in simulation with the above parameters) before it reaches the metasurface (e.g. the metasurface 122, 322) of the metalens. The propagation in the substrate may be segmented into eight stages in simulation, with a first shorter stage (e.g. $50\text{ }\mu\text{m}$ propagation distance in simulation with the above parameters), and a plurality of equal stages (e.g. seven $100\text{ }\mu\text{m}$ consecutive intervals in simulation with the above parameters). The output beam from the waveguide component is injected to the start of the first stage of the substrate as a mode source,

an output beam from the first stage is injected to the second stage, and so forth. That is, an output beam from a preceding stage is injected to a succeeding stage as a mode source.

[00076] As a result of collimation by the metalens, the divergence angles in x- and y-directions both decrease significantly. The distance between the metalens and the detection plane may be too long (e.g. 2 mm) to be numerically simulated with FDTD, the power collected by the detector (e.g. the detector 131) at the detection plane may be calculated by projecting the field shown in FIG. 6B. FIG. 6B shows the light beam has a divergence of 5.97° in the X-direction and has a divergence of 7.35° in the Y-direction after propagating through the metalens. The mid-IR detector may have a detection area of $400 \times 500 \mu\text{m}^2$.

[00077] Table 1 summarizes the power budget in the above simulation as well as the metalens efficiency and percentage of power collected by the detector at the end. As a result, it is found that the propagation loss along the substrate of the metalens is around 15% (i.e. by combining the losses from the first to eight stages of the substrate as shown in row 2, columns 2 to 9 of Table 1), which is partly due to material loss and partly due to the limited simulation volume. The metalens has a loss of around 30% (i.e. row 2, column 10 of Table 1), which can be attributed to the reflection at the Ge-air interface (i.e. the interface between the waveguide component (Ge) and the substrate of the metalens (Si)). Since the metalens collimates the light beam quite well, the power that is collected by the detector 2 mm away is almost 100% (i.e. row 2, column 11 of Table 1). The overall power efficiency of the optical unit is therefore calculated as 58.6% (i.e. row 2, column 12 of Table 1) for the optical unit with the metalens in contact with the waveguide component. The overall power efficiency of the optical unit of 42.6% may be obtained for the optical unit with the metalens spaced apart from the waveguide component (with a $0.5 \mu\text{m}$ gap).

[00078] Table 1. Power budget at different stages of beam propagation

Distance (z)	50 μm	150 μm	250 μm	350 μm	450 μm	550 μm	650 μm	750 μm	Metalens	2.75 mm detector (4 pixels)	Total
Efficiency (%)	99.07	99.39	99.54	99.06	98.78	97.69	93.33	99.60	70.2	99.2	58.6

[00079] FIGS. 7A and 7B show a 1-dimensional array of optical units 700 and a 2-dimensional array of optical units 750, respectively, according to various embodiments of the present disclosure. The optical units may be similar to the optical units 100, 300 as described herein.

[00080] As shown in FIG. 7A, the 1-dimensional array of optical units 700 may include a plurality of optical units (e.g. the optical units 100, 300) arranged along the X-direction. Each of the plurality of optical units may be spaced apart from another optical unit of the plurality of optical units at an equal distance.

[00081] According to various non-limiting embodiments, the plurality of optical unit may include a plurality of waveguide components (e.g. 702a, 702b, 702c, 702d), and a plurality of collimating metalens (e.g. including the metasurfaces 704a, 704b, 704c, 704d) optically coupled to the plurality of waveguide components, respectively. It shall be appreciated that number of the plurality of optical unit is not limited to four as shown in FIG. 7A but include any suitable number according to application requirements. The plurality of collimating metalens may be configured to respectively collimate, focus or expand light beam transmitted by the plurality of waveguide components on to a detection plane (not shown). Similarly, the plurality of waveguide components may include tapered waveguides (as shown in FIG. 7A), straight waveguides (not shown) or a mixture of tapered waveguides and straight waveguides (e.g. alternative tapered waveguide and straight waveguide). The equal distance between the plurality of optical units may be determined in a manner that a respective light beam transmitted by a respective waveguide component of the plurality of waveguide components may not interface with a neighboring light beam transmitted by a neighboring optical unit of the respective waveguide component of the plurality of waveguide components.

[00082] According to various non-limiting embodiments, the plurality of collimating metalens may include a plurality of metasurfaces (e.g. 704a, 704b, 704c, 704d), each having nanostructures extending toward the detection plane (not shown). In some embodiments, the plurality of collimating metalens may be arranged in the YZ-plane perpendicular to transmission/propagation directions (e.g. in the XZ-plane) of the light beam transmitted by the plurality of waveguide components.

[00083] According to various non-limiting embodiments, the plurality of collimating metalens may include a substrate 703 having a first surface 703a and an opposing second surface 703b. The first surface 703a of the substrate 703 may face the plurality of waveguide components and the second surface 703b may form a plurality of metasurfaces (e.g. 704a, 704b, 704c, 704d) having the nanostructures extending toward the detection plane. In other words, the plurality of metalens may have a common substrate 703.

[00084] According to various non-limiting embodiments, each of the plurality of metasurfaces (e.g. 704a, 704b, 704c, 704d) may have a plurality of nanopillars of different

diameters corresponding to different phase changes of the light beam transmitted by a corresponding waveguide component of the plurality of waveguide components so as to collimate, focus or expand the light beam on to the detection plane. In some embodiments, the plurality of nanopillars of one metasurface (e.g. 704a) and the plurality of nanopillars of another metasurface (e.g. 704c) may have a same set of different diameters. In other embodiments, the plurality of nanopillars of one metasurface (e.g. 704a) and the plurality of nanopillars of another metasurface (e.g. 704c) may have a different set of different diameters.

[00085] As shown in FIG. 7B, the 2-dimensional array of optical units 750 may include a plurality of optical units (e.g. the optical units 100, 300) arranged along the X-direction and the Y-direction. Each of the plurality of optical units may be spaced apart from another optical unit of the plurality of optical units along the X-direction at a first equal distance and from another optical unit of the plurality of optical units along the Y-direction at a second equal distance. In some embodiments, the first equal distance may be the same as the second equal distance. In other embodiments, the first equal distance may be different from the second equal distance. The 2-dimensional array of optical units 750 may include a plurality of the 1-dimensional array of optical units 700 arranged along the Y-direction.

[00086] While this specification contains many details, these should not be understood as limitations on the scope of what may be claimed, but rather as descriptions of features specific to particular examples. Certain features that are described in this specification or shown in the drawings in the context of separate implementations can also be combined. Conversely, various features that are described or shown in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination.

[00087] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single product or packaged into multiple products.

[00088] A number of implementations have been described. Nevertheless, it will be understood that various modifications can be made. Accordingly, other implementations are within the scope of the following claims.

CLAIMS

1. An optical unit comprising:
a waveguide component; and
a collimating metalens optically coupled to the waveguide component and configured to collimate, focus or expand light beam transmitted by the waveguide component on to a detection plane,
wherein the collimating metalens comprises a metasurface having nanostructures extending toward the detection plane.
2. The optical unit of claim 1, wherein the waveguide component comprises a tapered waveguide or a straight waveguide.
3. The optical unit of claim 1, wherein the waveguide component is an edge-coupler optically coupled to a photonic chip.
4. The optical unit of claim 1, wherein the collimating metalens is arranged in a direction non-parallel to transmission directions of the light beam transmitted by the waveguide component.
5. The optical unit of claim 1, wherein the collimating metalens comprises a substrate having a first surface and an opposing second surface, wherein the first surface of the substrate faces the waveguide and the second surface is the metasurface having the nanostructures extending toward the detection plane.
6. The optical unit of claim 5, wherein the first surface of the substrate of the collimating metalens is in contact with an output end of the waveguide component in a manner that the light beam transmitted by the waveguide component are incident on the first surface of the substrate of the collimating metalens.
7. The optical unit of claim 5, wherein the first surface of the substrate of the collimating metalens is spaced apart from an output end of the waveguide component in a manner that the light beam transmitted by the waveguide component are incident on the first surface of the substrate of the collimating metalens.

8. The optical unit of claim 6 or claim 7, wherein the metasurface of the collimating metalens is parallel with a facet of the output end of the waveguide component.
9. The optical unit of claim 6 or claim 7, wherein the light beam transmitted by the waveguide component include sub-beams, and the sub-beams are incident on the first surface at different oblique incident angles.
10. The optical unit of claim 7, wherein the first surface of the substrate of the collimating metalens is spaced apart from the output end of the waveguide component by a distance of $0.5\mu\text{m}$.
11. The optical unit of claim 1, wherein the nanostructures comprise cylindrical-shaped, square-shaped, triangular-shaped, rectangular-shaped, hexagonal-shaped pillars having a height between 0.4 and $4\mu\text{m}$, and a lateral size that varies between 0.1 and $2\mu\text{m}$.
12. The optical unit of claim 1, wherein the nanostructures are separated from nearest neighbor nanostructures by a gap of at least 60nm .
13. The optical unit of claim 1, wherein the nanostructures comprise a plurality of nanopillars of different diameters corresponding to different phase changes of the light beam transmitted by the waveguide component so as to collimate, focus or expand the light beam transmitted by the waveguide component on to the detection plane.
14. The optical unit of claim 1, wherein the nanostructures comprise a plurality of nanopillars having negative sidewall angles with a top radius greater than a bottom radius of the plurality of nanopillars.
15. The optical unit of claim 1, wherein an optical detector is provided at the detection plane to detect the collimated, focused or expanded light beam by the collimating metalens.

16. The optical unit of claim 11, wherein the optical detector comprises a gas or vacuum chamber provided between the collimating metalens and the optical detector.
17. The optical unit of claim 1, wherein the waveguide component and the nanostructures of the collimating metalens are made of a same material selected from Germanium (Ge), Si, Si_xO_y , Si_xN_y , and/or TiO_2 .
18. The optical unit of claim 1, wherein the substrate of the collimating metalens is made of a transparent material and a thickness of the substrate ranges from $500\mu\text{m}$ to 1mm .
19. The optical unit of claim 1, wherein the light beam transmitted by the waveguide component have a wavelength ranging from infrared to visible light.
20. A method for collimating, focusing or expanding light beam, the method comprising:
transmitting light beam by a waveguide component;
receiving the light beam from the waveguide component by a collimating metalens optically coupled to the waveguide; and
collimating, focusing or expanding, by the collimating metalens, the light beam received on to a detection plane,
wherein the collimating metalens comprises a metasurface having nanostructures extending toward the detection plane.