US012386119B2

(12) United States Patent
Liu et al.

(10) Patent No.: US 12,386,119 B2
(45) Date of Patent: Aug. 12, 2025

(54) **FACET PROFILE TO IMPROVE EDGE COUPLER BEAM POINTING AND COUPLING EFFICIENCY FOR PHOTONICS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 255 days.

(21) Appl. No.: **17/856,382**

(22) Filed: **Jul. 1, 2022**

(65) **Prior Publication Data**

US 2023/0314718 A1 Oct. 5, 2023

Related U.S. Application Data

(60) Provisional application No. 63/325,248, filed on Mar. 30, 2022.

(51) **Int. Cl.**

G02B 6/42	(2006.01)
G02B 6/12	(2006.01)
G02B 6/30	(2006.01)

(52) **U.S. Cl.**

CPC ***G02B 6/305*** (2013.01); ***G02B 6/12004*** (2013.01); ***G02B 6/4214*** (2013.01)

(58) **Field of Classification Search**

CPC G02B 6/421; G02B 6/4212; G02B 6/1228; G02B 6/122

See application file for complete search history.

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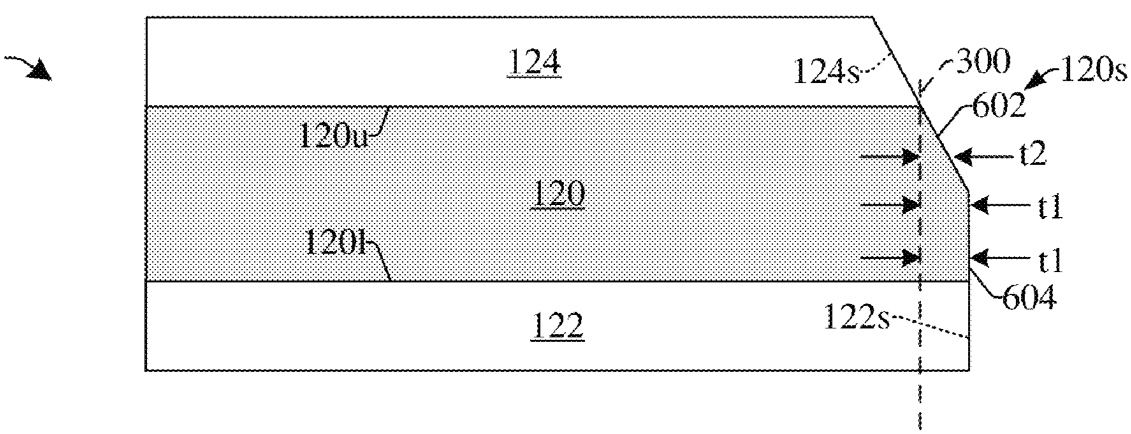
Primary Examiner — Eric Wong

(74) *Attorney, Agent, or Firm* — Eschweiler & Potashnik, LLC

(57) **ABSTRACT**

Various embodiments of the present disclosure are directed towards an integrated circuit. The integrated circuit includes a substrate having an upper face and a lower face. The upper face includes a central region and an outer sidewall that laterally surrounds the central region and that extends from the upper face to the lower face. An optical edge coupler is disposed over the upper face of the substrate and extends in a first direction from the central region toward the outer sidewall. An outer sidewall of the optical edge coupler corresponds to the outer sidewall of the substrate and has a concave surface or a convex surface.

20 Claims, 13 Drawing Sheets

112


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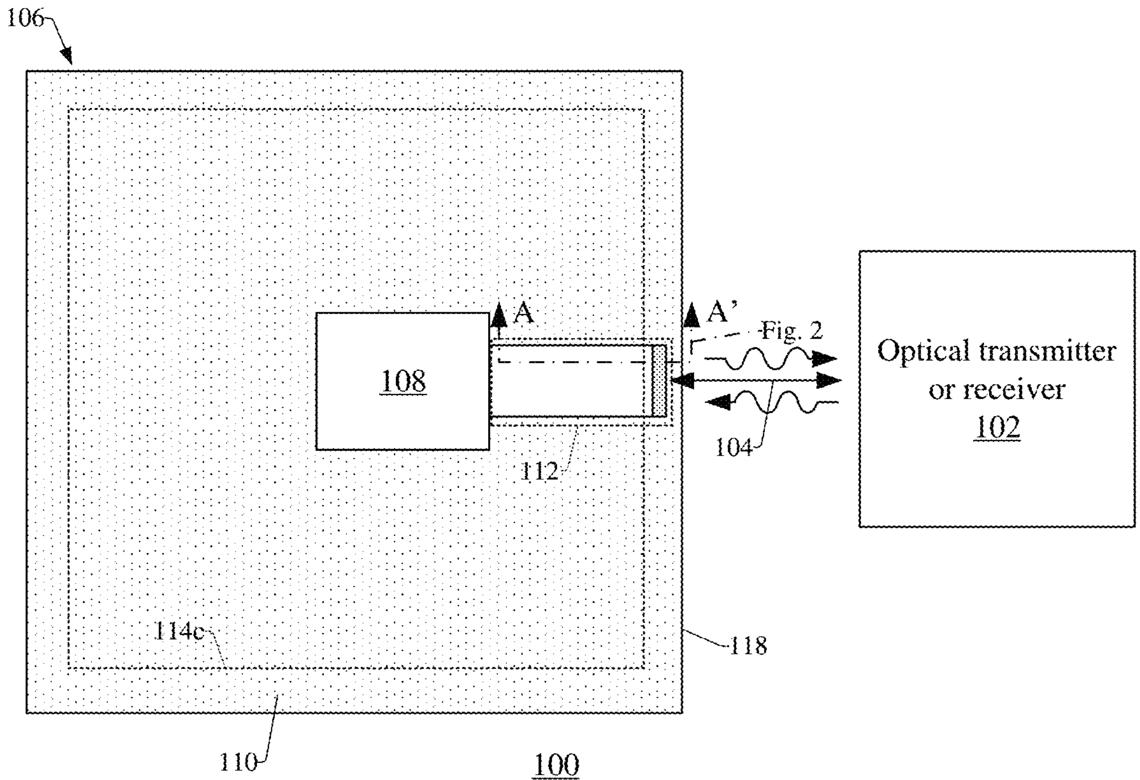

106
A
A'
Fig. 2
108
Optical transmitter
or receiver
102
104
112
114c
118
110
100

Fig. 1

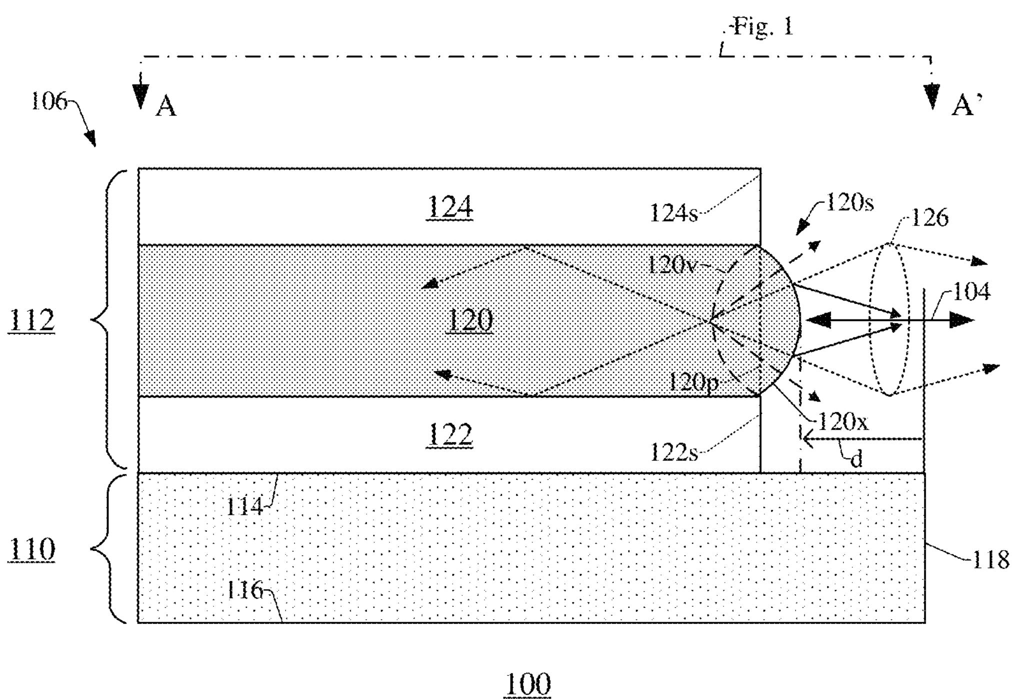
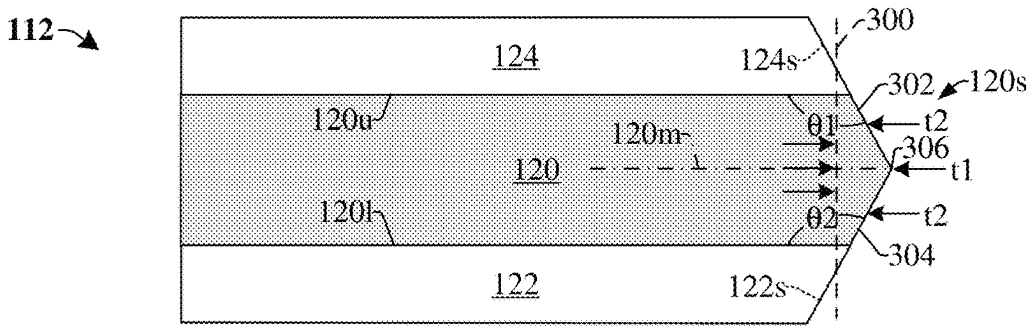


Fig. 1
A
A'
106
124
124s
120s
126
112
120v
104
120
120p
120x
122
122s
d
114
110
118
116
100

Fig. 2



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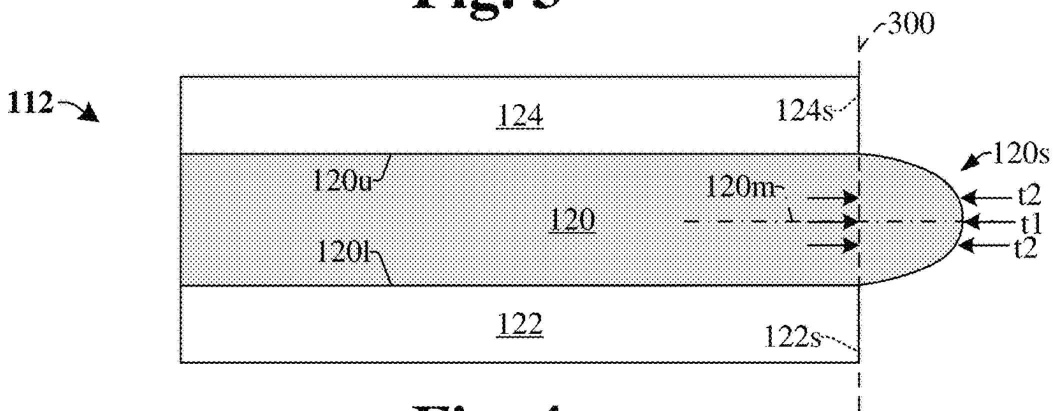

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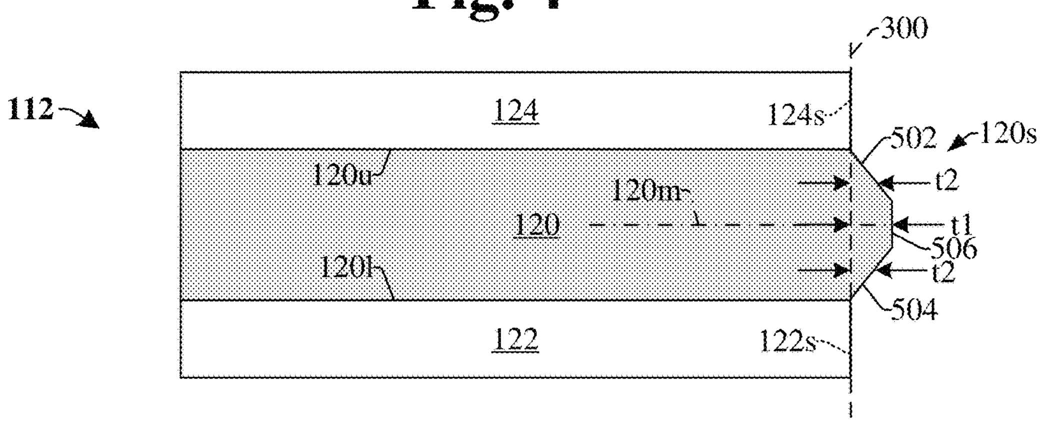

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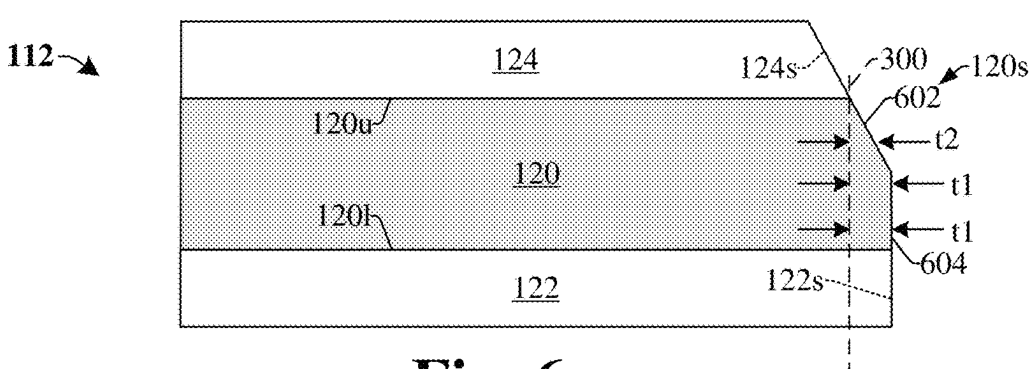

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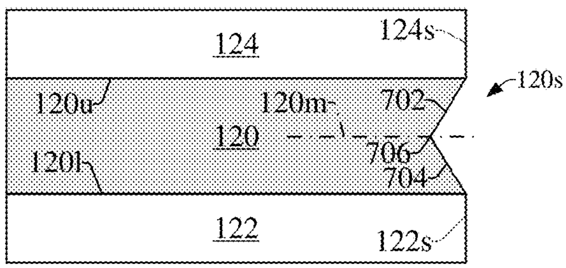

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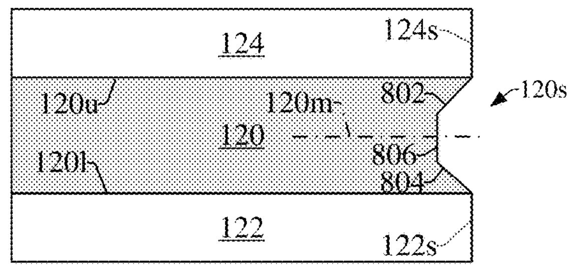

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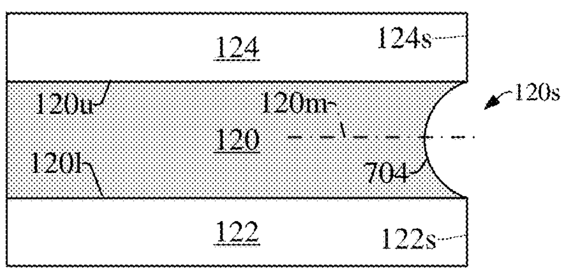

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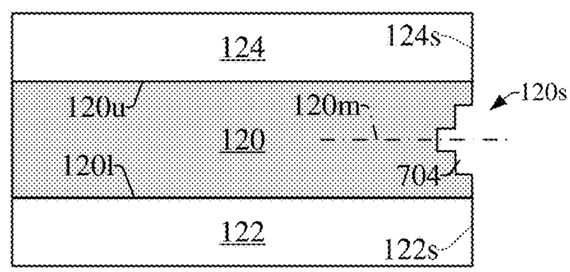

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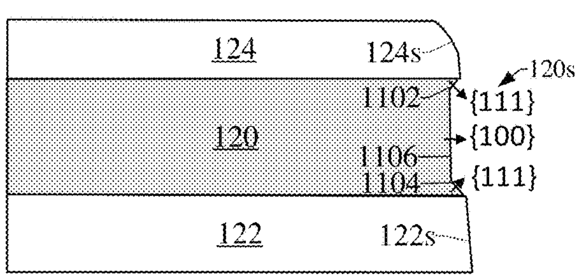

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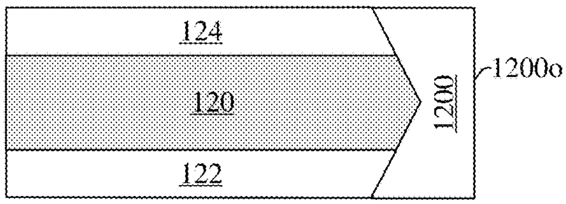

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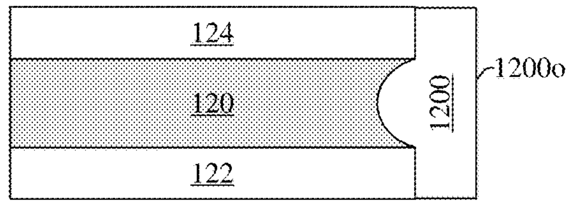

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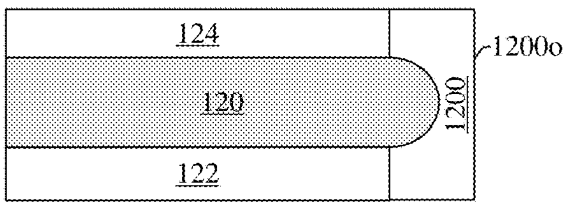

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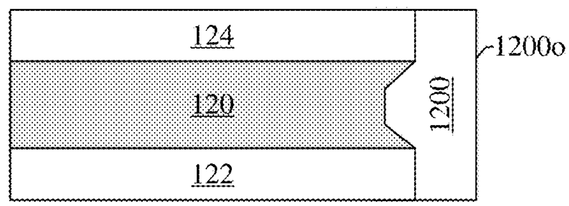

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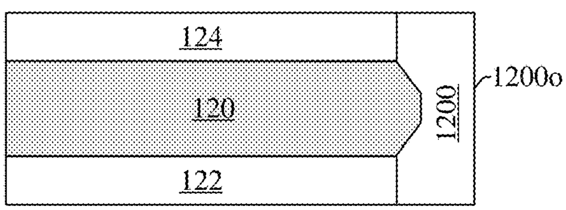

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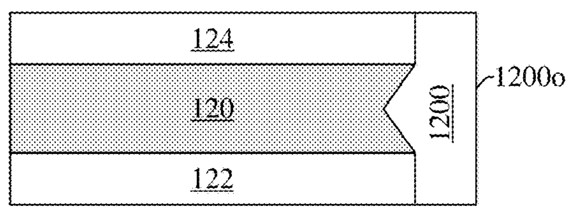

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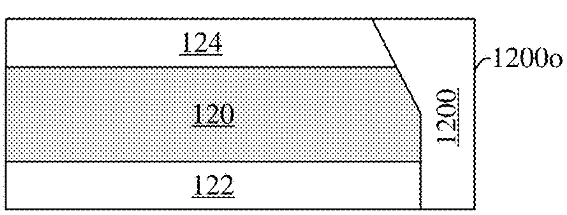

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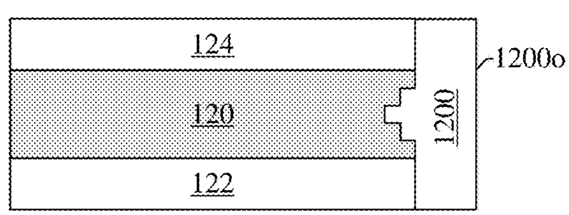

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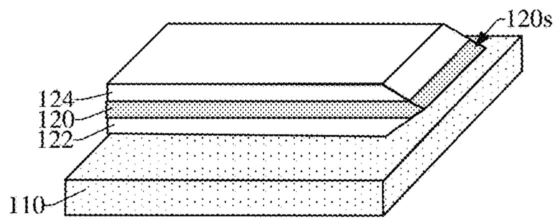

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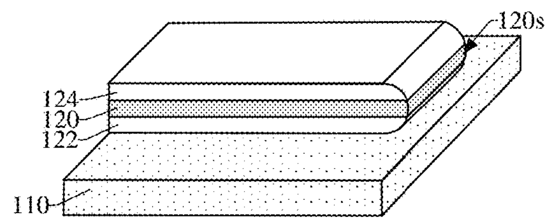

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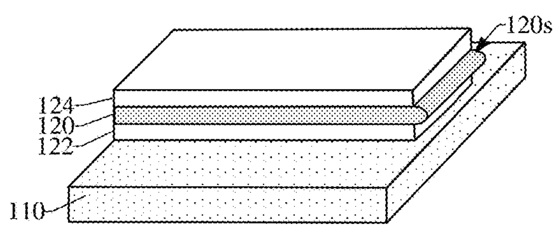

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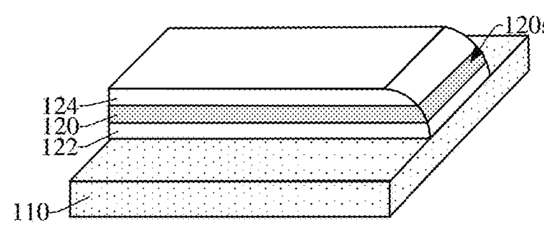

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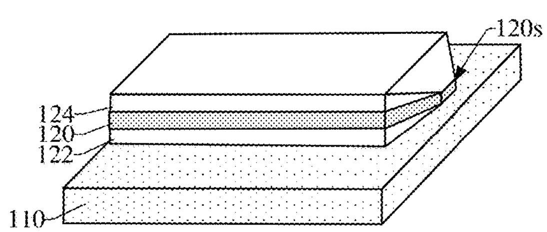

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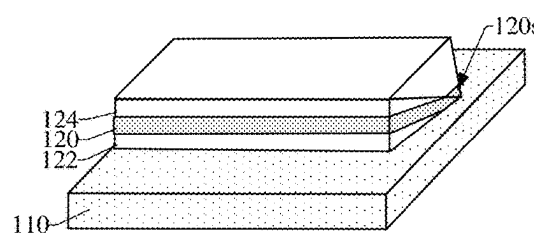

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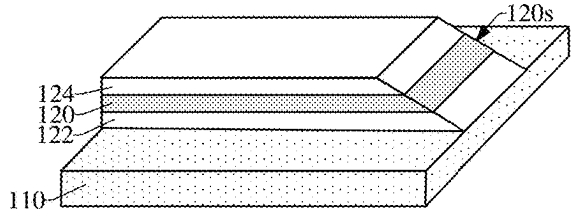

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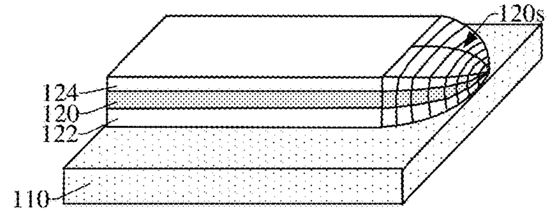

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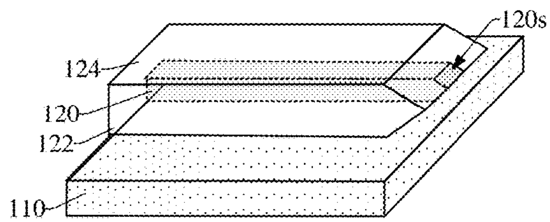

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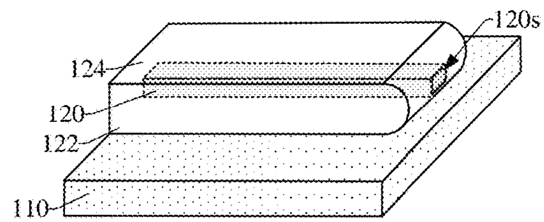

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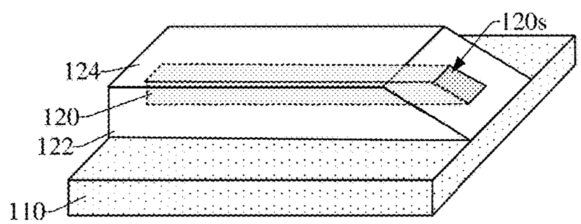

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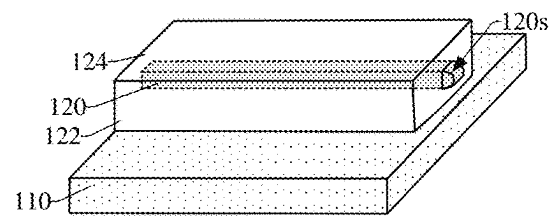

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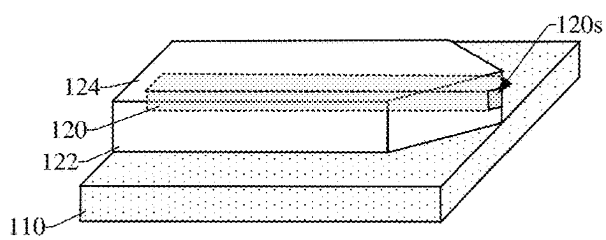

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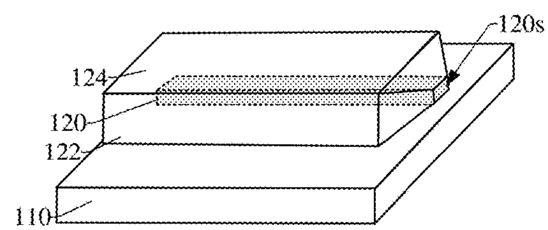

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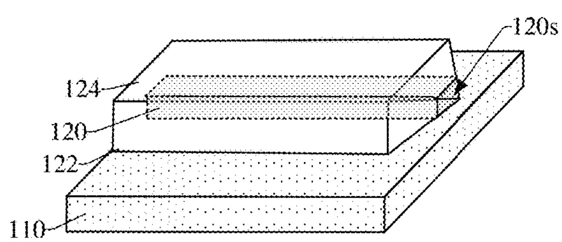

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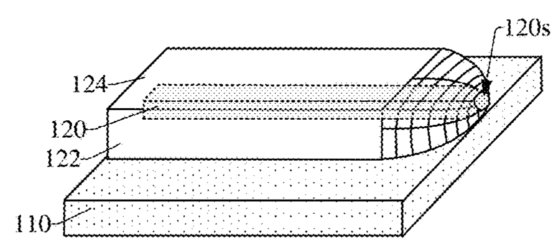

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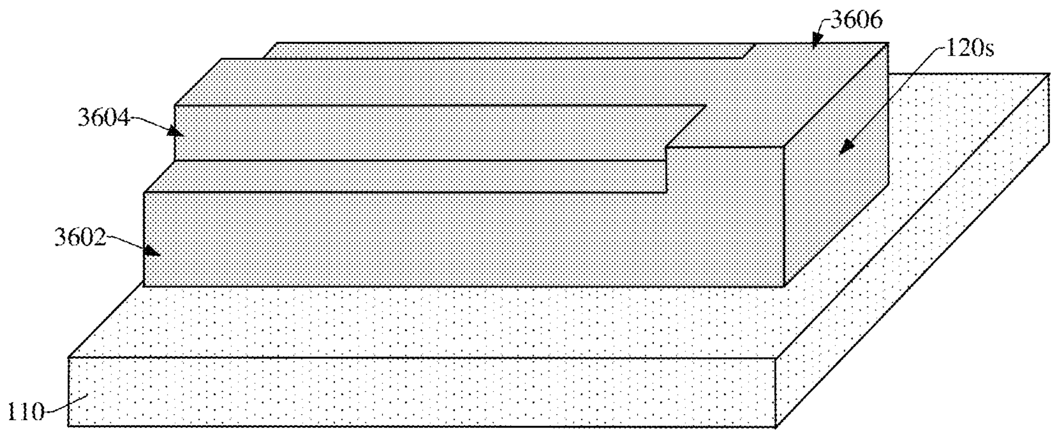

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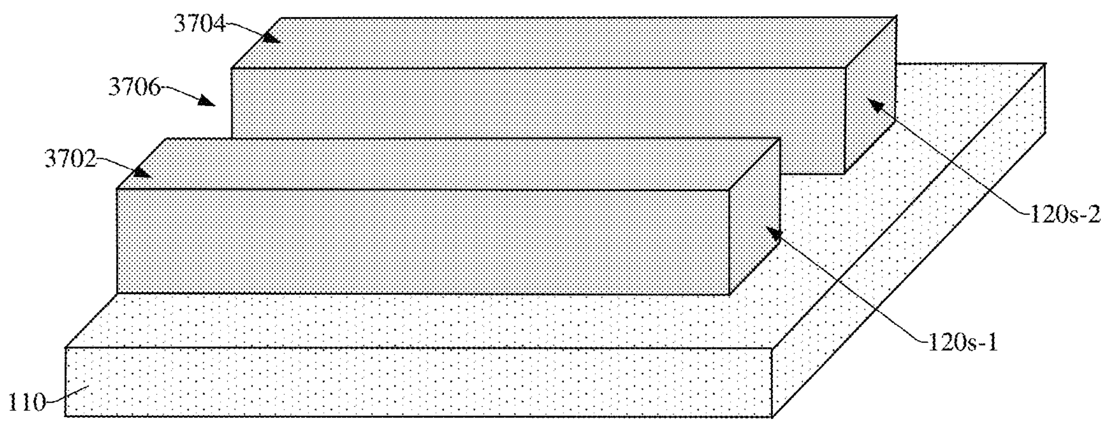

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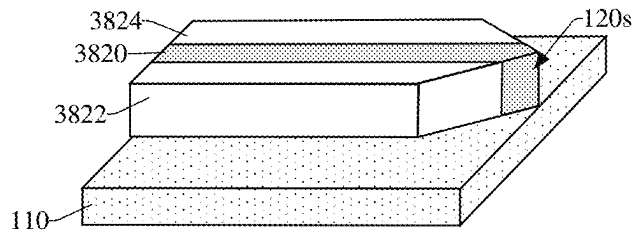

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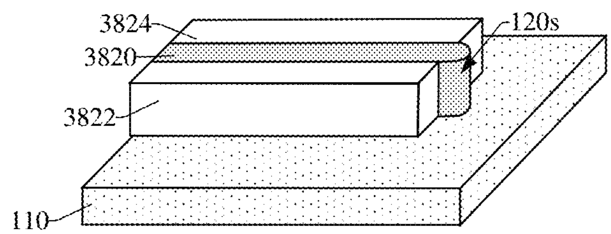

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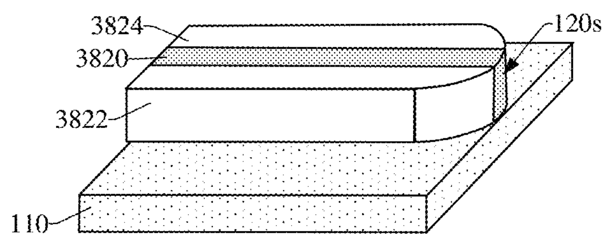

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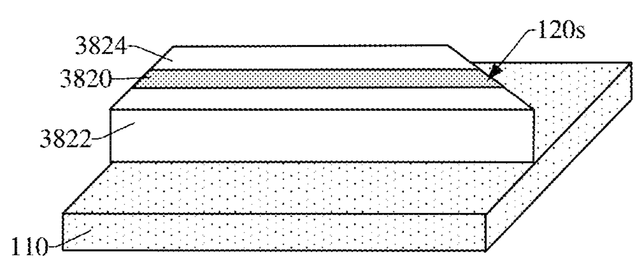

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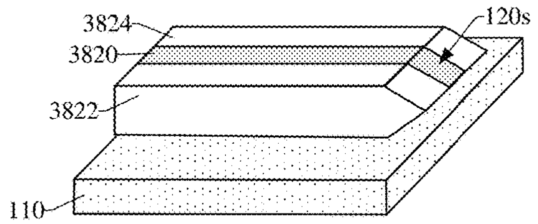

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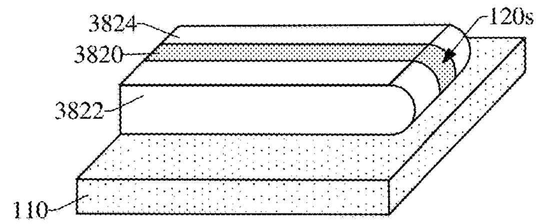

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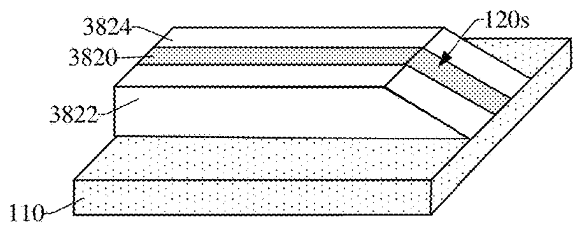

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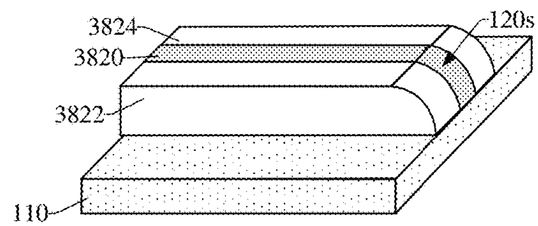

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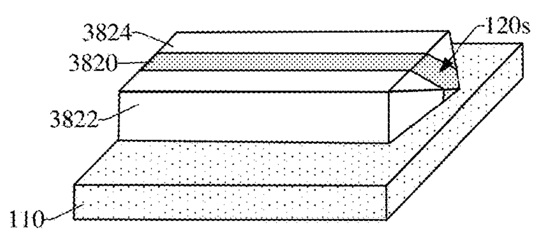

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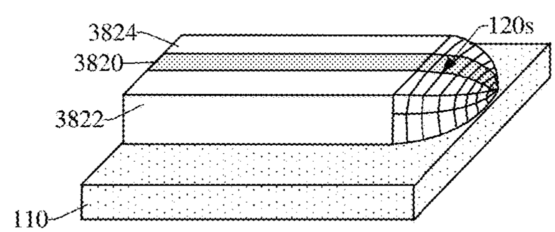

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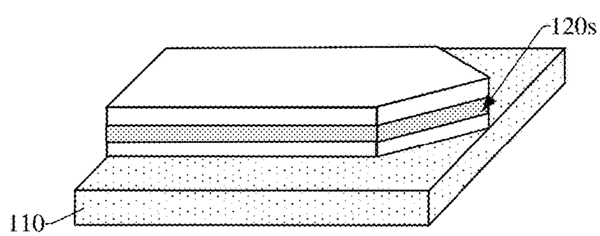

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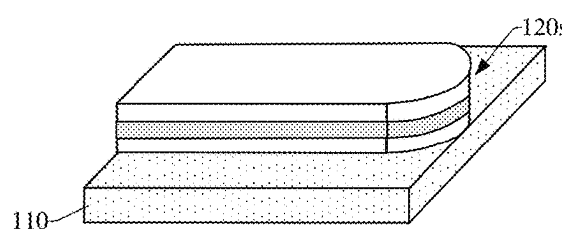

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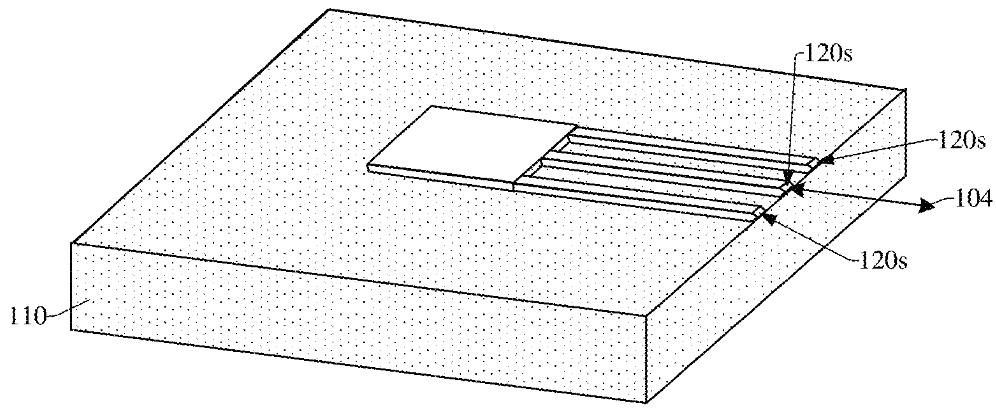

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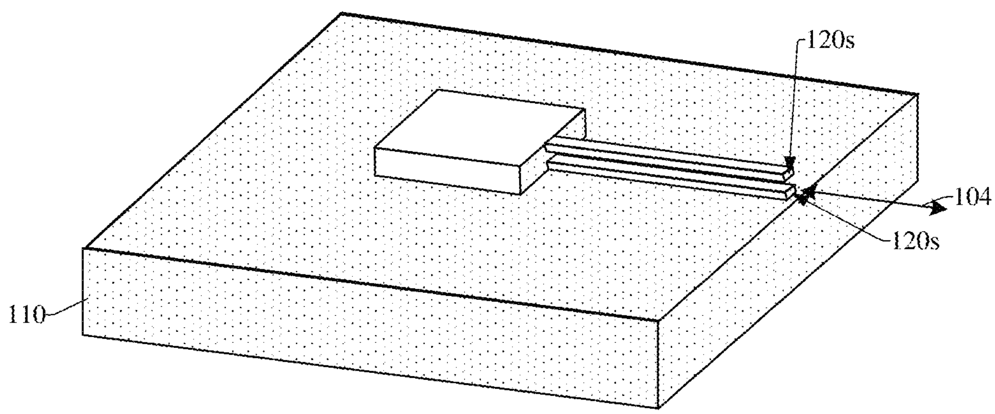

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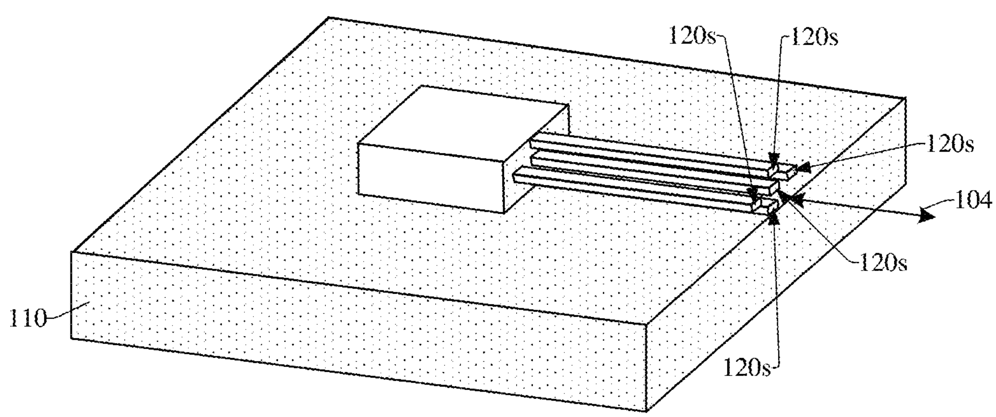

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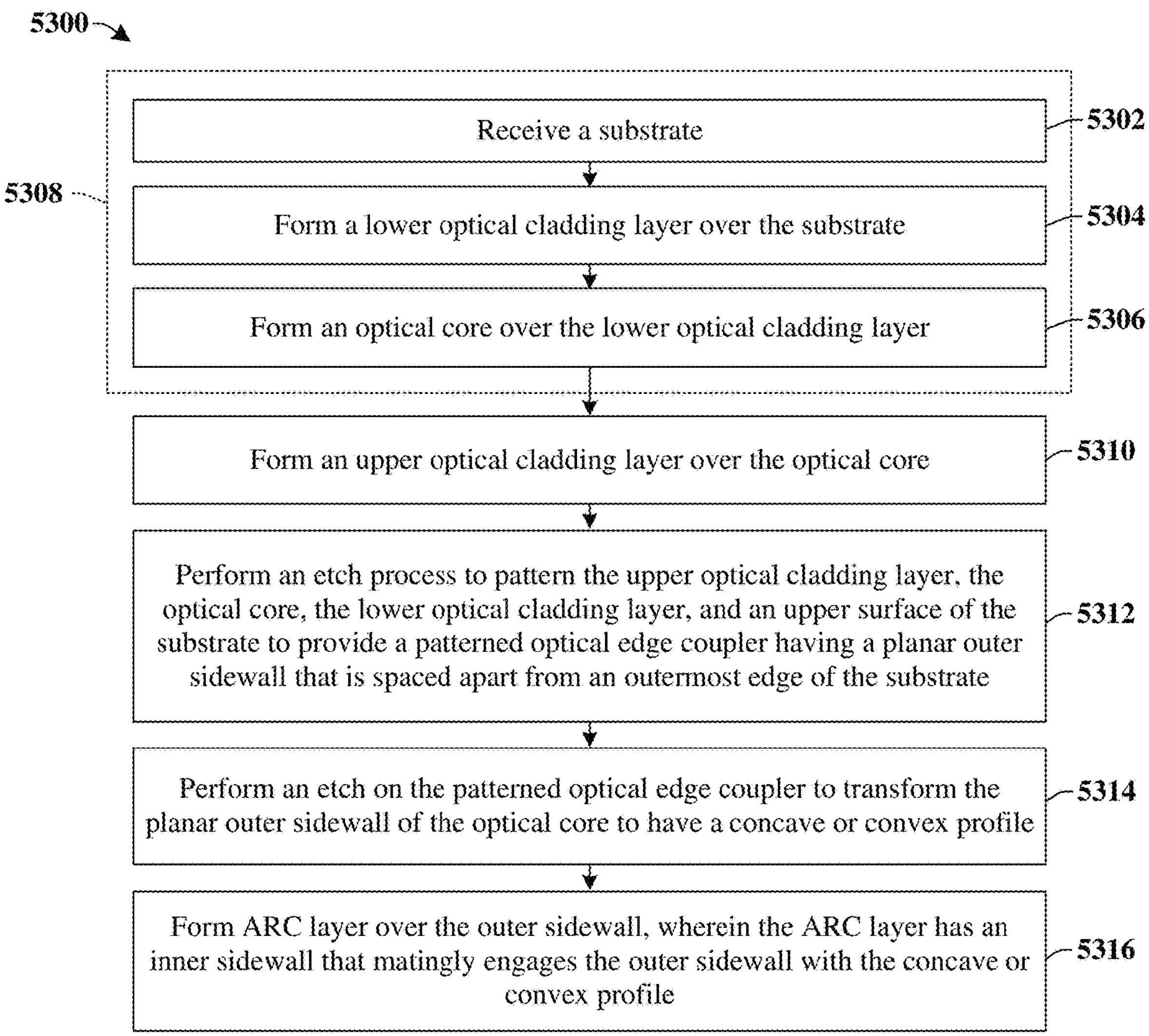
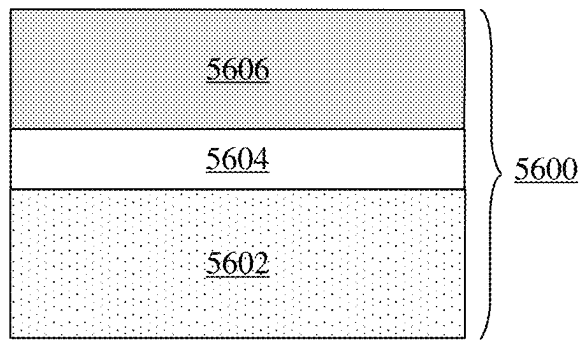

5300
5308
Receive a substrate
5302
Form a lower optical cladding layer over the substrate
5304
Form an optical core over the lower optical cladding layer
5306
Form an upper optical cladding layer over the optical core
5310
Perform an etch process to pattern the upper optical cladding layer, the optical core, the lower optical cladding layer, and an upper surface of the substrate to provide a patterned optical edge coupler having a planar outer sidewall that is spaced apart from an outermost edge of the substrate
5312
Perform an etch on the patterned optical edge coupler to transform the planar outer sidewall of the optical core to have a concave or convex profile
5314
Form ARC layer over the outer sidewall, wherein the ARC layer has an inner sidewall that matingly engages the outer sidewall with the concave or convex profile
5316

Fig. 53



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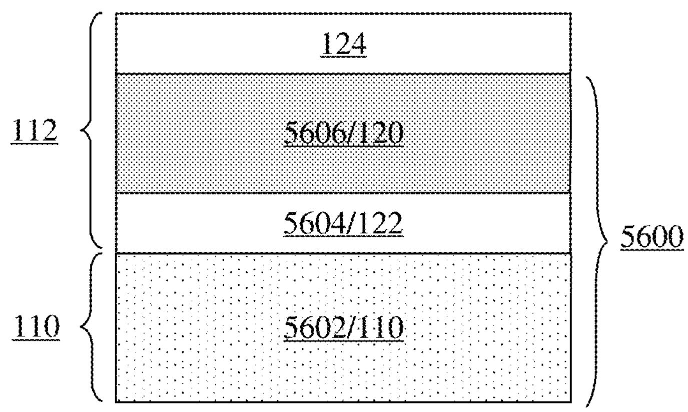

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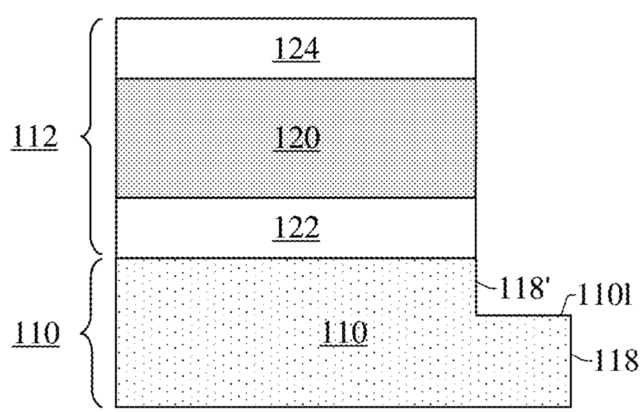

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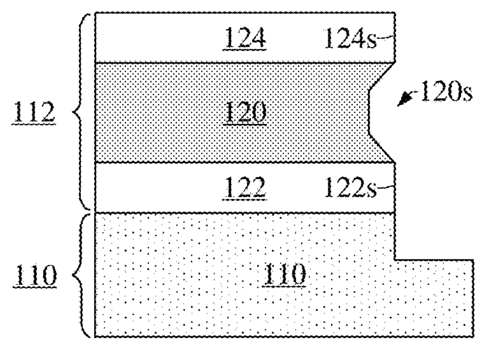

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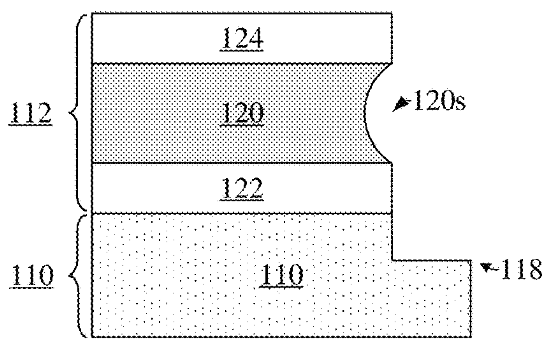

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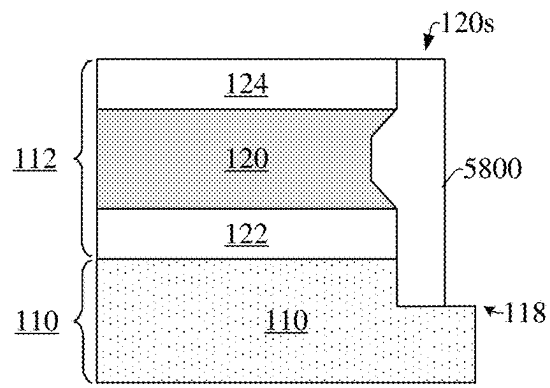

Fig. 58B

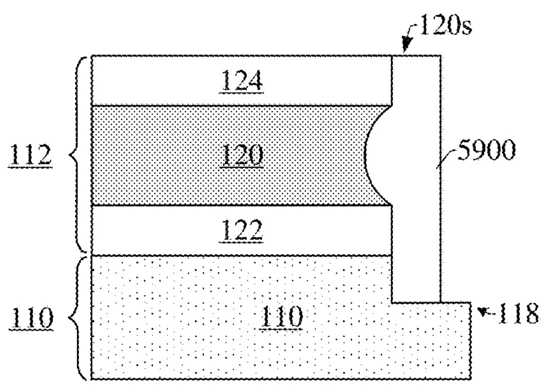

Fig. 59

FACET PROFILE TO IMPROVE EDGE COUPLER BEAM POINTING AND COUPLING EFFICIENCY FOR PHOTONICS

REFERENCE TO RELATED APPLICATION

This Application claims the benefit of U.S. Provisional Application No. 63/325,248, filed on Mar. 30, 2022. The contents of the above-referenced Patent Application is hereby incorporated by reference in its entirety.

BACKGROUND

Optical edge couplers are often used as components in integrated optical circuits, which integrate multiple photonic functions. Optical edge couplers are used to confine and guide light from a first point on an integrated chip (IC) to a second point on the IC with minimal attenuation. Generally, optical edge couplers provide functionality for signals imposed on optical wavelengths in the visible spectrum (e.g., between approximately 850 nm and approximately 1650 nm), but some optical edge couplers can also provide functionality for signals in other regions of the electromagnetic spectrum.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. **1** illustrates a top view of some embodiments of an optical edge coupler.

FIG. **2** illustrates a cross-sectional view of some embodiments consistent with the optical edge coupler of FIG. **1**.

FIGS. **3-6** illustrate cross-sectional views of some embodiments of optical edge couplers that each include a convex outer sidewall.

FIGS. **7-11** illustrate cross-sectional views of some embodiments of optical edge couplers that each include a concave outer sidewall.

FIGS. **12-19** illustrate cross-sectional views of some embodiments of optical edge couplers that include an optical core having a concave or convex outer sidewall and an anti-reflecting coating (ARC) layer having an inner sidewall that matingly engages the concave or convex outer sidewall of the optical core.

FIGS. **20-27** illustrate perspective views of some embodiments of optical edge couplers in the form of slab waveguides that each include a convex outer sidewall.

FIGS. **28-35** illustrate perspective views of some embodiments of optical edge couplers in the form of channel waveguides that each include a convex outer sidewall.

FIG. **36** illustrates a perspective view of some embodiments of a rib waveguide that includes a concave or convex outer sidewall.

FIG. **37** illustrates a perspective view of some embodiments of a slot waveguide that includes two segments that each include a concave or convex outer sidewall.

FIGS. **38-49** illustrate perspective views of some additional embodiments of optical edge couplers.

FIGS. **50-52** illustrate perspective views of some additional embodiments of optical edge couplers.

FIG. **53** illustrates a flow diagram of a method of manufacturing an optical edge coupler in accordance with some embodiments.

FIGS. **54**, **55**, **56**, **57**, **58**A-**58**B, and **59** show a series of cross-sectional views that collectively depict some manufacturing methods in accordance with some embodiments.

DETAILED DESCRIPTION

The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

Optical edge couplers can provide high speed signal communication using light or other electromagnetic waves. Typically, the use of light or other electromagnetic waves provides lower power consumption and less heating than conventional electrical signals.

FIG. **1** and FIG. **2**, which show a top view and corresponding cross-sectional view and are now described concurrently, show an example of an optical system **100** according to some embodiments. The optical system **100** includes an optical transmitter or receiver **102**, such as a chip, optical fiber, or other component, which is configured to transmit and/or receive an optical signal along an optical communication path **104**. An integrated circuit **106** is configured to interact with the optical transmitter or receiver **102** through the optical communication path **104**. In some embodiments, the integrated circuit **106** can include circuitry or other structures **108** that can generate optical signals, detect optical signals, analyze optical signals, modify optical signals, transfer optical signals, and/or transform optical signals to electrical signals (or vice versa); thereby enabling communication and/or signal processing between the integrated circuit **106** and the optical transmitter or receiver **102**.

The integrated circuit **106** includes a substrate **110**, which has an upper face **114** and a lower face **116**, and an optical edge coupler **112** disposed on the upper face **114** of the substrate **110**. The upper face **114** includes a central region **114***c*, and an outer sidewall **118** laterally surrounds the central region **114***c* and extends from the upper face **114** to the lower face **116**. The optical edge coupler **112** is disposed over the upper face of the substrate and extends in a first direction from the central region **114**c toward the outer sidewall **118**.

The optical edge coupler includes an optical core **120**, a lower optical cladding layer **122** separating the optical core **120** from the substrate **110**, and an upper optical cladding layer **124** disposed over the optical core **120**. The optical core **120** is disposed over the substrate **110** and is aligned to the optical communication path **104** of the optical transmitter or receiver **102**. The optical core **120** has a first index of refraction. The lower optical cladding layer **122** has a second index of refraction that is less than the first index of refraction. The upper optical cladding layer **124** also typically has the second index of refraction.

The optical core **120** has an outer sidewall **120**s that is located on the optical communication path **104**. Thus, when a signal is transmitted and/or received on the optical communication path **104** between the optical transmitter or receiver **102** and the integrated circuit **106**, the signal enters and/or exits the optical core **120** through the outer sidewall **120**s. The outer sidewall **120**s generally corresponds to the outer sidewall **118** of the substrate **110**, and can have an outermost point that is recessed from the outer sidewall **118** of the substrate **110** by distance d or that is aligned with (e.g., co-planar) with the outer sidewall **118** of the substrate **110**. This outer sidewall **120**s can have various profiles depending on the implementation. In some embodiments, the substrate **110**, optical core **120**, and lower optical cladding layer **122** are formed from a silicon on insulator (SOI) substrate, with the substrate **110** corresponding to a handle substrate of the SOI substrate, lower optical cladding layer **122** corresponding to an insulating layer of the SOI substrate, and optical core **120** corresponding to a silicon device layer of the SOI substrate.

In some cases, the outer sidewall **120**s of the optical core **120** has a planar profile **120**p that is aligned with corresponding outer sidewalls (**122**s, **124**s) of the lower and upper optical cladding layers (**122**, **124**, respectively). However, to realize favorable transfer efficiency between the integrated circuit **106** and the optical transmitter or receiver **102** with such a planar profile **120**p, a lens **126** is typically inserted along the optical communication path **104** in such cases.

As has been appreciated in some aspects of the present disclosure, changing the profile of the outer sidewall **120**s of the optical core **120** to be concave or convex can improve beam pointing and coupling efficiency of the optical edge coupler **112**, thereby limiting the need for the lens **126**. Thus, some embodiments can reduce costs and manufacturing complexity by having no lens between the optical edge coupler **112** and the optical transmitter or receiver **102**. It will be appreciated that the term "concave or convex" as used in this disclosure is not limited to curved surfaces that have a single radius of curvature, but can also include surfaces that have multiple planar facets, multiple radii of curvature, and/or combinations of one or more planar facet (s) and one or more radius (radii) of curvature. Thus, the concave or convex sidewall may include any protrusion shape, including a triangle, a polygon, a portion of a circle or oval, etc.

As illustrated in FIG. **2**, when the outer sidewall **120**s has a convex profile **120**x, the convex profile **120**x promotes beam pointing, which may be advantageous when light propagating in to or out of the optical edge coupler is to be narrower (e.g., more focused) away from the outer sidewall **120**s than when a planar sidewall **120**p is used. Further, when the outer sidewall **120**s has a concave profile **120**v, the concave profile **120**v promotes beam widening, which may be advantageous when light propagating in to or out of the optical edge coupler is to be wider (e.g., more diffuse) away from the outer sidewall **120**s than when a planar sidewall **120**p is used.

In some embodiments, the optical core **120** is made of a first material and the lower optical cladding layer **122** and/or upper optical cladding layer **124** are made of a second material. The first material can have a first index of refraction that is greater than a second index of refraction of the second material. For example, in some cases the first index of refraction is between 25% larger and 300% larger than the second index of refraction, or is between 50% larger and 150% larger than the second index of refraction. In some embodiments, the first material can comprise monocrystalline silicon, polycrystalline silicon, amorphous silicon, or silicon nitride (e.g., Si3N4) and can have a refractive index of ranging between about 2 and about 3.5, and the second material can comprise silicon dioxide and can have a refractive index of between 1.4 and 1.5. In some embodiments, the substrate **110** is a monocrystalline silicon substrate.

Further in some embodiments, the thickness of the optical core **120**, lower optical cladding layer **122**, and upper optical cladding layer **124** can be approximately equal as measured perpendicular to the upper surface **114** of the substrate **110**; however in other embodiments the optical core **120**, lower optical cladding layer **122**, and upper optical cladding layer **124** can have different thicknesses. Thus, in some cases where the substrate is a silicon on insulator (SOI) substrate and the optical core **120** corresponds to a silicon/device layer of the SOI substrate and the lower optical cladding layer **122** corresponds to an insulator layer of the SOI substrate, the upper optical cladding layer **124** can be thinner than the optical core **120** and lower optical cladding layer **122**. For example, in some embodiments, the optical core **120** can have a thickness of about approximately 3 micrometers+/−0.1 micrometers, the lower optical cladding layer **122** can have a thickness of about 2 micrometers+/−0.1 micrometers, and the upper optical cladding layer **124** can have a thickness of about 1.5 micrometers+/−0.1 micrometers. While some waveguides and/or optical couplers according to this disclosure have upper and lower optical cladding layers of the same thickness, it has been appreciated that leaving the upper optical cladding layer **124** thinner than the lower optical cladding layer **122** provides manufacturing efficiencies that are not achieved with equal thicknesses for the upper and lower optical cladding layers.

Referring now to FIGS. **3-6** collectively, one can see various cross-sectional views of some embodiments of optical edge couplers **112** that each include an outer sidewall **120**s having a convex profile. In each illustrated example, an outer sidewall **120**s of the optical core **120** protrudes outward past at least one of an outer sidewall **124**s of the upper optical cladding layer **124** and/or an outer sidewall **122**s of the lower optical cladding layer **122**. Further, the outer sidewall **124**s of the upper optical cladding layer **124** and/or the outer sidewall **122**s of the lower optical cladding layer **122** are traversed by a plane **300**, and the optical core **120** has a varying thickness as measured perpendicular to the plane **300** from the lower optical cladding layer **122** to the upper optical cladding layer **124**. Thus, the convex profile of the optical core **120** has varying thicknesses at various heights in the optical core (e.g., a first thickness t1 and second thickness t2, wherein t1>t2)

In FIG. **3**, the outer sidewall **120**s, which is convex, comprises an upper planar facet **302** and a lower planar facet **304** that meet at a point **306**. In FIG. **3**'s example, the point **306** is disposed along a mid-line **120**m of the optical core.

The mid-line **120***m* is equally spaced between an upper surface **120***u* of the optical core and a lower surface **120***l* of the optical core. The upper planar facet **302** meets the upper surface **120***u* of the optical core at a first angle, θ1, and the lower planar facet **304** meets the lower surface **120***l* of the optical core at a second angle, θ2. In some embodiments, θ1 and θ2 are each greater than 90 degrees, and are equal to one another, thereby giving the optical edge coupler **112** a symmetry about a mid-line **120***m* that runs along a length of the optical core. In some cases, θ1 and θ2 can range between 92 degrees and 150 degrees, but other ranges are also possible. Further, the outer sidewall **124***s* of the upper optical cladding layer is planar with the upper planar facet **302**, and the outer sidewall **122***s* of the lower optical cladding layer is planar with the lower planar facet **304**, though in other embodiments these surfaces could be offset or "kinked" relative to one another.

In FIG. **4**, the outer sidewall **120***s* is a continuous curved surface in the form of an ellipse or oval that extends from the lower optical cladding layer **122** to the upper optical cladding layer **124**. Thus, as the illustrated outer sidewall **120***s* in FIG. **4** is an ellipse or oval, the radius of curvature of the outer sidewall **120***s* varies at different points on the outer sidewall. In other embodiments, the continuously curved surface could take the form of a semicircle or portion of a circle or portion of a sphere, which has a single, fixed radius of curvature over the entire curve. In FIG. **4**, the outer sidewall **124***s* of the upper optical cladding layer **124** and outer sidewall **122***s* of the lower optical cladding layer **122** are co-planar with one another, though they could also be angled/tapered, such as shown in FIG. **3** for example.

In FIG. **5**, the outer sidewall **120***s* comprises an upper planar facet **502** and a lower planar facet **504** that meet at an intermediate planar facet **506**. The intermediate planar facet **506** is traversed by the mid-line **120***m* of the optical core. In FIG. **4**, the outer sidewalls of the upper and lower cladding layers are co-planar with one another (and along plane **300**), though they could also be angled/tapered, such as shown in FIG. **3** for example.

In FIG. **6**, the outer sidewall **120***s* comprises an upper planar facet **602** and a lower planar facet **604**. The lower planar facet **604** is co-planar with the outer sidewall **122***s* of the lower optical cladding layer. Thus, the lower planar facet **604** and outer sidewall of the lower optical cladding layer are vertical and are perpendicular with respect to an upper surface of the substrate (not shown). In other embodiments, the outer sidewall **124***s* of the upper optical cladding layer could also be vertical and could correspond to plane **300**.

FIGS. **7-11** illustrate cross-sectional views of some embodiments of optical edge couplers **112** that each include an optical core **120** having an outer sidewall with a concave profile. Thus, in each of FIGS. **7-11**, an outer sidewall **124***s* of the upper optical cladding layer **124** and/or an outer sidewall **122***s* of the lower optical cladding layer **122** protrudes outwardly past an outer sidewall **120***s* of the optical core **120**, giving rise to a concave profile.

In FIG. **7**, the concave outer sidewall **120***s* comprises an upper planar facet **702** and a lower planar facet **704** that meet at a point **706**. In FIG. **7**'s example, the point **706** is disposed along a mid-line of the optical core and is equally spaced between an upper surface **120***u* of the optical core and a lower surface **120***l* of the optical core. The upper planar facet **702** meets the upper surface **124***u* of the optical core at a first angle, θ1, and the lower planar facet **704** meets the lower surface **120***l* of the optical core at a second angle, θ2. In some embodiments, θ1 and θ2 are each less than 90 degrees and are equal to one another, thereby giving the optical edge coupler **112** a symmetry about a mid-line **120***m* that runs along a length of the optical core. In some cases, θ1 and θ2 can range between 88 degrees and 40 degrees, but other ranges are also possible. Further, the outer sidewalls of the upper optical cladding layer **124** and lower optical cladding layer **122** are illustrated as being vertical and thus non-planar with the upper planar facet **702** and lower planar facet **704**, though in other embodiments the outer sidewall **124***s* of the upper optical cladding layer **124** could be co-planar with the upper planar facet **702** and the outer sidewall **122***s* of the lower optical cladding layer **122** could be co-planar with the lower planar facet **704**.

In FIG. **8**, the outer sidewall **120***s* comprises an upper planar facet **802** and a lower planar facet **804** that meet at an intermediate planar facet **806**. The intermediate planar facet **806** is disposed along the mid-line **120***m* of the optical core. In FIG. **20**, the outer sidewalls **122***s*, **124***s* of the lower and upper cladding layers are co-planar with one another, though they could also be angled/tapered, such as shown in FIG. **3** for example.

In FIG. **9**, the outer sidewall **120***s* is a continuous curved surface in the form of a portion of a circle that extends from the lower optical cladding layer **122** to the upper optical cladding layer **124**. Thus, the continuously curved surface is illustrated as a circle or portion of a sphere, and has a single, fixed radius of curvature over the entire curve. In other embodiments, the outer sidewall **120***s* could be an ellipse or oval, which has a radius of curvature of the sidewall varies at different points on the concave outer sidewall.

FIG. **10**, the outer sidewall **120***s* includes a series of discrete steps or cubes that increase in depth from the upper surface **120***u* and lower surface **120***l* to the mid-line **120***m*. Each step includes a horizontal surface and a vertical surface, which can be of equal length and can meet one another at about 90 degrees.

FIG. **11** depicts an example somewhat similar to FIG. **8** in that the outer sidewall **120***s* comprises an upper planar facet **1102** and a lower planar facet **1104** that meet at an intermediate planar facet **1106**. In FIG. **11**, however, the upper planar facet **1102** and lower planar facet **1104** are disposed along a **111** plane of the crystal of the optical core **120**, and the intermediate planar facet **1106** is disposed along a **100** plane of the crystal of the optical core. Further, the upper optical cladding layer **124** has an outer sidewall **124***s* that is tapered so a portion nearest the optical core extends outwardly further than a portion furthest from the optical core. The lower optical cladding layer **122** has an outer sidewall **122***s* that is angled, but is not symmetric with the sidewall of the upper optical cladding layer **124**.

FIGS. **12-19** illustrate cross-sectional views of some embodiments of optical edge couplers that include an anti-reflective coating (ARC) layer **1200** arranged on the outer sidewall **120***s*. Thus, in each of FIGS. **12-19**, the ARC layer **1200** has an inner sidewall that matingly engages the outer sidewall of the optical edge coupler. The ARC layer **1200** has a third index of refraction that is less than the index of refraction of the optical core **120** and greater than that of air (or whatever ambient environment surrounds the optical edge coupler). In some cases, this third index of refraction can also be less than the index of refraction of the upper and/or lower optical cladding layers **122**, **124**, can be equal to the index of refraction of the upper and/or lower optical cladding layers **122**, **124**, or can be greater than the index of refraction of the upper and/or lower optical cladding layers **122**, **124**. In the illustrated embodiments, the ARC layer **1200** has varying thicknesses along the outer sidewall of the optical edge coupler such that an outer sidewall of the anti-reflective coating terminates in a planar surface **1200***o*. The ARC layer **1200** can be a single film or can include multiple layers that are stacked over the outer sidewall **120***s*. If multiple layers are used, each layer is orientated in a generally vertical direction (e.g., covering the outer sidewall of the optical core and outer sidewalls of upper and lower optical cladding layers).

FIGS. **20-27** illustrate perspective views of some embodiments of optical edge couplers in the form of a "slab" waveguide that each include a convex outer sidewall **120***s*. FIGS. **20-23** are generally consistent with FIGS. **3-6**, and depict an optical core **120** sandwiched between a lower optical cladding layer **122** and an upper optical cladding layer **124**. Each depicted slab waveguide extends generally in a first direction (e.g., left to right on the page), and has planar sidewalls that extend in parallel with the first direction, as well as a planar top surface. In FIG. **24**, the upper and lower optical cladding layers are rounded so the outer sidewall profile of the optical edge coupler is a continuous curve with an outermost extent that corresponds to the optical core **120**. In FIG. **25**, the upper and lower optical cladding layers are rounded so the outer sidewall profile of the optical edge coupler is a continuous curve, but here the outermost extent of the outer sidewall corresponds to the bottom of lower optical cladding layer **122**. In FIG. **26**, the outer sidewall of the optical core terminates at a point, and in FIG. **27**, the outer sidewall is rounded or sphere-like when viewed in perspective. Although FIGS. **20-27** depict examples corresponding to convex outer sidewalls, the concave profiles (see e.g., FIGS. **7-11**) could also be used, and/or an ARC layer can be disposed on the outer sidewalls (see e.g., FIGS. **12-19**).

FIGS. **28-35** illustrate perspective views of some embodiments of channel waveguides that each include a convex outer sidewall. Compared to a slab waveguide (see e.g., FIGS. **20-27** where the optical core is sandwiched between an upper and lower optical cladding layer), a channel waveguide has the optical core axially surrounded on all sides by an optical cladding material having a lower index of refraction than the optical core. Though the channel waveguides are illustrated as having convex outer sidewalls in FIGS. **28-35**, the outer sidewall of the optical core can alternatively have a concave profile (see e.g., FIGS. **7-11**), and/or an ARC layer can be disposed on the outer sidewalls (see e.g., FIGS. **12-19**) to provide a high optical coupling efficiency with other components.

FIG. **36** illustrates a perspective view of some embodiments of a rib waveguide **3600** that includes an outer sidewall **120***s* having a concave or convex profile. The rib waveguide includes an optical core **120** with a base **3602** and a rib **3604** extending upwards from an upper portion of the base **3602**. The rib **3604** perpendicularly meets an end cap structure **3606** that is also arranged over the base. The rib waveguide includes an outer sidewall **120***s* that has a convex or concave profile, such as illustrated for example in FIGS. **3-35** or other profiles illustrated and/or described herein.

FIG. **37** illustrates a perspective view of some embodiments of a slot waveguide **3700** that includes a first segment **3702** and a second segment **3704** that extend in parallel in a first direction with a slot **3706** between them over an upper surface of a substrate **110**. The first segment **3702** includes a first outer sidewall **120***s***-1** having a first concave or convex profile, and the second segment **3704** includes a second outer sidewall **120***s***-2** that also has the same concave or convex profile. Thus, in some instances, the first and second outer sidewalls can have the same convex or concave profile, such as illustrated for example in FIGS. **3-35** or other profiles illustrated and/or described herein, while in other cases the first and second outer sidewalls can have different profiles from one another.

FIGS. **38-47** illustrate perspective views of some additional embodiments of optical edge couplers. In these cases, the optical edge coupler includes an optical core **3820** with an outer sidewall **120***s* having a concave or convex profile. However, rather than having an upper optical cladding layer and a lower optical cladding layer as illustrated in previous embodiments, the optical edge couplers of FIGS. **38-47** include a left optical cladding layer **3822** and a right optical cladding layer **3824** that are arranged at the same height over the substrate **110**.

FIGS. **48-49** illustrate perspective views of some additional embodiments of optical edge couplers. In FIGS. **48-49**, the optical edge couplers again have an optical core that is sandwiched between a lower optical cladding layer and an upper optical cladding layer, but here, the convex profile is viewed along a cross-section taken in parallel with an upper surface of the substrate **110**. Additional convex profiles and/or concave profiles (optionally with an ARC layer), such as previously illustrated and/or described could also be orientated in this manner, with FIGS. **48-49** merely being non-limiting examples.

FIGS. **50-52** illustrate perspective views of some additional embodiments of optical edge couplers. As shown in FIG. **50**, an optical edge coupler or waveguide can include multiple branches disposed on or over an upper surface of the substrate **110** and spaced horizontally from one another. Each branch can terminate in an outer sidewall **120***s* having a concave or convex profile, and can optionally be covered by an ARC layer.

As shown in FIG. **51**, an optical edge coupler or waveguide can include multiple branches disposed on or over an upper surface of the substrate **110** and spaced vertically from one another. Each branch can terminate in an outer sidewall **120***s* having a concave or convex profile, and can optionally be covered by an ARC layer.

As shown in FIG. **52**, an optical edge coupler or waveguide can include multiple branches disposed on or over an upper surface of the substrate **110**, with the branches spaced laterally and horizontally from one another. Each branch can terminate in an outer sidewall **120***s* having a concave or convex profile, and can optionally be covered by an ARC layer.

FIG. **53** illustrates a flow diagram of a method of manufacturing an optical edge coupler in accordance with some embodiments.

At **5302**, a substrate is received.

At **5304**, a lower optical cladding layer is formed over the substrate.

At **5306**, an optical core is formed over the lower optical cladding layer. As indicated by **5308**, in some embodiments, **5302**, **5304**, and **5306** occur by a fabrication facility that delivers a semiconductor on insulator (SOI) substrate with a semiconductor handle wafer, insulator layer over the semiconductor handle wafer, and semiconductor device layer over the insulator layer. Thus, in some instances, the method **5300** starts by simply obtaining an SOI substrate, where the substrate of **5302** corresponds to a handle substrate of the SOI substrate, the lower optical cladding layer corresponds to the insulator layer of the SOI substrate, and the optical core corresponds to the semiconductor device layer of the SOI substrate.

At **5310**, an upper optical cladding layer is formed over the optical core.

At **5312**, an etch process is performed to pattern the upper optical cladding layer, the optical core, the lower optical cladding layer, and an upper surface of the substrate to provide a patterned optical edge coupler having an outer sidewall that is spaced apart from an outermost edge of the substrate.

At **5314**, an etch is performed on the patterned optical edge coupler to re-shape an outer sidewall of the optical core relative to an outer sidewall of the lower optical cladding layer and an outer sidewall of the upper optical cladding layer. In this way, an outer sidewall with a concave or convex profile can be formed for the optical edge coupler.

In some cases, the etch in **5314** is a wet etch that results in the outer sidewall of the optical core having multiple planar facets (e.g., 111 planar facet and 100 planar facet) that meet at respective intersection points. Optionally following such a wet etch, an annealing operation is performed to reflow material of the optical core to transform the multiple planar facets into a continuous curved surface between the upper optical cladding layer and the lower optical cladding layer.

In **5316**, an ARC layer is optically formed over the outer sidewall, with the ARC layer having an inner sidewall that matingly engages the outer sidewall of the optical core.

FIGS. **54**, **55**, **56**, **57**, **58**A-**58**B, and **59** show a series of cross-sectional views the collectively depict some manufacturing methods in accordance with some embodiments.

In FIG. **54**, a substrate **5600** is received. In the illustrated example, the received substrate is a semiconductor on insulator (SOI) substrate with a semiconductor handle wafer, insulator layer over the semiconductor handle wafer, and semiconductor device layer over the insulator layer. The semiconductor handle wafer typically comprises monocrystalline silicon, the insulator layer comprises silicon dioxide or a high-k dielectric layer, and the semiconductor device layer comprises silicon or silicon nitride.

In FIG. **55**, an upper optical cladding layer **124** is formed over the semiconductor device layer. The upper optical cladding layer is an insulating material and can have the same material composition as the insulator layer in some cases. Thus, the upper optical cladding layer can comprise silicon dioxide or high-k dielectric material in some embodiments. Notably, in FIG. **57**, the reference numerals reflect a change in nomenclature that the handle wafer **5602** may be referred to as a substrate **110**, while the insulator layer **5604** may be referred to as a lower optical cladding layer **122** and the device layer **5606** may be referred to as an optical core **120**. The lower optical cladding layer **122**, optical core **120**, and upper optical cladding layer **124** can be included in an optical edge coupler **112** disposed over the substrate **110**.

In FIG. **56**, a first etch process is performed to pattern the upper optical cladding layer **124**, the optical core **120**, the lower optical cladding layer **122**, and an upper portion of the substrate **110** to provide a patterned optical edge coupler having an outer sidewall **118'** that is spaced apart from an outer sidewall **118** of the substrate. Typically, the first etch process includes forming a mask over the upper optical cladding layer **124**, wherein the mask covers some portions of the upper optical cladding layer **124** and leaves others portions of the upper optical cladding layer exposed, and performing an etch to remove the exposed portions of the upper optical cladding layer and underlying portions of the optical core **120**, lower optical cladding layer **122**, and portions of the substrate **110**. The outer sidewall **118'** formed by this first etch process can be a substantially planar sidewall and can extend from the upper surface of the upper optical cladding layer **124** to a ledge **1101** formed in the substrate **110**. In some cases, the first etching process can include a dry etch, but other etches could also be used.

In FIG. **57**, a second etch process is performed on the outer sidewall **118'** to re-shape an outer sidewall **120*s*** of the optical core **120** relative to an outer sidewall **122*s*** of the lower optical cladding layer **122** and an outer sidewall **124*s*** of the upper optical cladding layer **124**. In this way, an outer sidewall **120*s*** with a concave or convex profile can be formed for the optical edge coupler. In some cases, this second etch process is a wet etch in the form of a tetramethyl ammonium hydroxide (TMAH) etch. In some cases, the second etch process results in the outer sidewall of the optical core having multiple planar facets (e.g., 111 planar facet and 100 planar facet).

In FIG. **58**A, which can optionally follow from FIG. **57**, an annealing operation is performed to reflow material of the optical core **120** to transform the multiple planar facets on the outer sidewall **120*s*** into a continuous curved surface between the upper optical cladding layer and the lower optical cladding layer.

In FIG. **58**B, which can alternatively follow from FIG. **57**, an ARC layer **5800** is formed on the facets of the outer sidewall **120*s*** shown in FIG. **57**. The ARC layer has an inner sidewall that matingly engages the facets on the outer sidewall of the optical core.

In FIG. **59**, which can optically follow from FIG. **58**A, an ARC layer **5900** is formed on the continuous curved surface of the outer sidewall **120*s*** shown in FIG. **58**A. The ARC layer has an inner sidewall that matingly engages the continuous curved surface on the outer sidewall of the optical core.

Various embodiments of the present disclosure are directed towards an integrated circuit. The integrated circuit includes a substrate having an upper face and a lower face. The upper face includes a central region and an outer sidewall that laterally surrounds the central region and that extends from the upper face to the lower face. An optical edge coupler is disposed over the upper face of the substrate and extends in a first direction from the central region toward the outer sidewall. An outer sidewall of the optical edge coupler corresponds to the outer sidewall of the substrate and has a concave surface or a convex surface.

Other embodiments relate to an optical system that includes an optical transmitter or receiver comprising an optical communication path. An integrated circuit includes a substrate and an optical core over the substrate. The optical core has a first index of refraction and is aligned to the optical communication path of the optical transmitter or receiver. A lower optical cladding layer is disposed over the substrate and separates the substrate from the optical core. The lower optical cladding layer has a second index of refraction that is less than the first index of refraction. An upper optical cladding layer is disposed over the optical core. The upper optical cladding layer has the second index of refraction. The optical core has a concave or convex sidewall that corresponds to an outer edge of the substrate and is aligned to the optical communication path of the optical transmitter or receiver.

Still other embodiments relate to a method. In the method, a substrate is received. The substrate includes a base substrate, a lower optical cladding layer over the base substrate, and an optical core over the lower optical cladding layer. An upper optical cladding layer is formed over the optical core. An etch process is performed to pattern the upper optical cladding layer, the optical core, the lower optical cladding layer, and an upper surface of the substrate to provide a patterned optical edge coupler having an outer sidewall with a substantially planar profile and that is spaced apart from an outermost edge of the substrate. A wet etch is performed on the patterned optical edge coupler to recess an outer sidewall of the optical core relative to an outer sidewall of the lower optical cladding layer and an outer sidewall of the upper optical cladding layer.

The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. An optical system, comprising:

an optical transmitter or receiver comprising an optical communication path; and

an integrated circuit, comprising:

a substrate;

an optical core over the substrate, the optical core having a first index of refraction and being aligned to the optical communication path of the optical transmitter or receiver;

a lower optical cladding layer over the substrate and separating the substrate from the optical core, the lower optical cladding layer having a second index of refraction that is less than the first index of refraction; and

an upper optical cladding layer over the optical core, the upper optical cladding layer having the second index of refraction, wherein an outermost sidewall of the upper optical cladding layer is co-planar with a sidewall of the optical core, wherein the sidewall of the optical core intersects an upper surface of the optical core at an obtuse angle; and

wherein the optical core is aligned to the optical communication path of the optical transmitter or receiver.

2. An optical system, comprising:

an optical transmitter or receiver comprising an optical communication path; and

an integrated circuit, comprising:

a substrate;

an optical core over the substrate, the optical core having a first index of refraction and being aligned to the optical communication path of the optical transmitter or receiver;

a lower optical cladding layer over the substrate and separating the substrate from the optical core, the lower optical cladding layer having a second index of refraction that is less than the first index of refraction; and

an upper optical cladding layer over the optical core, the upper optical cladding layer having the second index of refraction, wherein an outermost sidewall of the upper optical cladding layer is co-planar with a sidewall of the optical core, wherein the sidewall of the optical core intersects an upper surface of the optical core at an obtuse angle; and

wherein the optical core is aligned to the optical communication path of the optical transmitter or receiver, wherein there is no lens on the optical communication path between the optical transmitter or receiver and the optical core.

3. The optical system of claim **1**, wherein the integrated circuit further comprises circuitry or other structures operably coupled to the optical transmitter or receiver via the optical communication path, the circuitry or other structures configured to generate, detect, analyze, modify, and/or redirect electromagnetic radiation to or from the optical transmitter or receiver.

4. The optical system of claim **1**, wherein the integrated circuit further comprises:

an anti-reflective coating arranged on the sidewall of the optical core, the anti-reflective coating having an inner sidewall that matingly engages the sidewall of the optical core and having varying thicknesses along the sidewall of the optical core such that an outer sidewall of the anti-reflective coating terminates in a planar surface.

5. The optical system of claim **4**, wherein the anti-reflective coating extends from an upper surface of the upper optical cladding layer to a lower surface of the lower optical cladding layer.

6. An optical system, comprising:

an optical transmitter or receiver comprising an optical communication path; and

an integrated circuit, comprising:

a substrate;

an optical core over the substrate, the optical core having a first index of refraction and being aligned to the optical communication path of the optical transmitter or receiver;

a lower optical cladding layer over the substrate and separating the substrate from the optical core, the lower optical cladding layer having a second index of refraction that is less than the first index of refraction; and

an upper optical cladding layer over the optical core, the upper optical cladding layer having the second index of refraction, wherein an outermost sidewall of the upper optical cladding layer is co-planar with a sidewall of the optical core, wherein the sidewall of the optical core intersects an upper surface of the optical core at an obtuse angle; and

wherein the optical core is aligned to the optical communication path of the optical transmitter or receiver, wherein the optical core protrudes outwardly past the outermost sidewall of the upper optical cladding layer and an outermost sidewall of the lower optical cladding layer.

7. The optical system of claim **1**, wherein the optical core further comprises a lower sidewall disposed vertically between the sidewall of optical core and a lower surface of the optical core, wherein the lower sidewall of the optical core is co-planar with an outermost sidewall of the lower optical cladding layer.

8. The optical system of claim **2**, wherein the integrated circuit further comprises circuitry or other structures operably coupled to the optical transmitter or receiver via the optical communication path, the circuitry or other structures configured to generate, detect, analyze, modify, and/or redirect electromagnetic radiation to or from the optical transmitter or receiver.

9. The optical system of claim **2**, wherein the integrated circuit further comprises:

an anti-reflective coating arranged on the sidewall of the optical core, the anti-reflective coating having an inner sidewall that matingly engages the sidewall of the optical core and having varying thicknesses along the sidewall of the optical core such that an outer sidewall of the anti-reflective coating terminates in a planar surface.

10. The optical system of claim **9**, wherein the anti-reflective coating extends from an upper surface of the upper optical cladding layer to a lower surface of the lower optical cladding layer.

11. The optical system of claim **6**, wherein the optical core further comprises a lower sidewall disposed vertically between the sidewall of optical core and a lower surface of the optical core, wherein the lower sidewall of the optical core is co-planar with an outermost sidewall of the lower optical cladding layer.

12. The optical system of claim **6**, wherein the integrated circuit further comprises circuitry or other structures operably coupled to the optical transmitter or receiver via the optical communication path, the circuitry or other structures configured to generate, detect, analyze, modify, and/or re-direct electromagnetic radiation to or from the optical transmitter or receiver.

13. The optical system of claim **6**, wherein the integrated circuit further comprises:

an anti-reflective coating arranged on the sidewall of the optical core, the anti-reflective coating having an inner sidewall that matingly engages the sidewall of the optical core and having varying thicknesses along the sidewall of the optical core such that an outer sidewall of the anti-reflective coating terminates in a planar surface.

14. The optical system of claim **13**, wherein the anti-reflective coating extends from an upper surface of the upper optical cladding layer to a lower surface of the lower optical cladding layer.

15. The optical system of claim **1**, wherein the first index of refraction is between 25% larger and 300% larger than the second index of refraction, or is between 50% larger and 150% larger than the second index of refraction.

16. The optical system of claim **1**, wherein the optical core comprises monocrystalline silicon, polycrystalline silicon, amorphous silicon, or silicon nitride, and the upper optical cladding layer and/or lower optical cladding layer comprises silicon dioxide.

17. The optical system of claim **1**, wherein the optical core has a refractive index of ranging between about 2 and about 3.5, and the upper optical cladding layer and/or lower optical cladding layer has a refractive index of between 1.4 and 1.5.

18. The optical system of claim **1**, wherein the substrate is a monocrystalline silicon substrate.

19. The optical system of claim **1**, wherein the substrate is a semiconductor on insulator substrate.

20. The optical system of claim **1**, wherein the optical core has a thickness of about approximately 3 micrometers +/− 0.1 micrometers, the lower optical cladding layer has a thickness of about 2 micrometers +/− 0.1 micrometers, and the upper optical cladding layer has a thickness of about 1.5 micrometers +/− 0.1 micrometers.

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