(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
09 May 2019 (09.05.2019)

WIPO | PCT

(10) International Publication Number
WO 2019/089221 A1

(51) International Patent Classification:
*G02B 6/32* (2006.01)

(21) International Application Number:
PCT/US2018/056058

(22) International Filing Date:
16 October 2018 (16.10.2018)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/579,396 31 October 2017 (31.10.2017) US

(71) Applicant: **ALLIANCE FIBER OPTIC PRODUCTS, INC.** [US/US]; 275 Gibraltar Drive, Sunnyvale, California 94089 (US).

(72) Inventors: **GUI, Dong**; 2744 Royalvale Way, San Jose, California 95132 (US). **LI, Yao**; 35669 Scarborough Drive, Newark, California 94560 (US). **XIA, Chen**; 39134 Cindy St., Fremont, California 94538 (US). **XIAO, Shudong**; 3750 Tamayo St., Apt. 122, Fremont, California 94536 (US). **ZHANG, Shiping**; Rm. 401, #242 Anyuanxiniu, Dongchengqu, Donguan, Xinqichaoshi, Guangdong 523000 (CN). **ZHOU, Andy Fenglei**; 41484 Mahoney St., Freemont, California 94538 (US).

(74) Agent: **BRANHAM, Robert L.**; CORNING OPTICAL COMMUNICATIONS LLC, Intellectual Property Department SP-TI-03-1, Corning, New York 14831 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH,

(54) Title: TUNED HIGH-DENSITY COLLIMATOR AND METHOD FOR TUNING



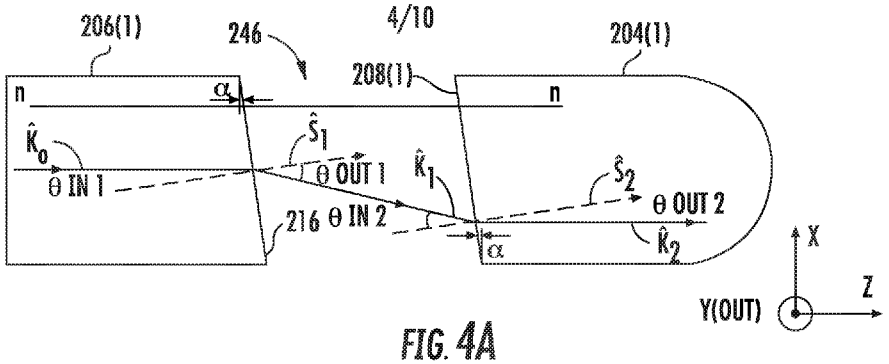


FIG. 4A

(57) Abstract: A tuned high-density collimator is disclosed herein. A collimating lens is secured to a mount and includes a first interface and defines a first central axis. A pigtail includes a ferrule secured to the mount and an optical fiber having a portion positioned within the ferrule. The ferrule defines a second central axis aligned with the first central axis of the collimating lens along a z-axis perpendicular to a y-axis. The optical fiber includes an end face at least partially defining a second interface. The first interface of the collimating lens and/or the second interface of the pigtail is planar and non-perpendicular to the z-axis. The collimating lens and the pigtail are rotationally oriented around the z-axis relative to each other such that a light pointing angle of an optical light path within the collimating lens is perpendicular to the y-axis.

WO 2019/089221 A1

[Continued on next page]

GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

**Published:**

— *with international search report (Art. 21(3))*

# TUNED HIGH-DENSITY COLLIMATOR AND METHOD FOR TUNING

## PRIORITY APPLICATION

**[0001]** This application claims the benefit of U.S. Provisional Application No. 62/579,396, filed on October 31, 2017, the content of which is relied upon and incorporated herein by reference in its entirety.

## BACKGROUND

**[0002]** The present disclosure relates generally to micro-optical systems, and particularly relates to tuned high-density collimators and methods for tuning.

**[0003]** Micro-optical systems employ optical elements that typically range in size from a few microns to a few millimeters and are used in a variety of optical and optical-electrical technologies and applications that require a small foot print or small form factor. With the increasing miniaturization of many types of optical and optical-electrical devices and systems, increasing demands are being placed on the size, performance, and integration requirements of micro-optical systems.

**[0004]** An example application where micro-optical systems are seeing increased use and increasing demands on size, performance, and integration is optical telecommunications. As high-speed optical telecommunications and data communications evolve, multiple wavelength channels are becoming widely adopted even in short-distance data center applications. As a result, multiplexer/de-multiplexer (Mux/DeMux) devices that employ micro-collimators and optical wavelength filters are becoming an important component in optical modules, such as C-form factor pluggable (CFP) optical modules, to functionally combine/split multiple optical signals, each operating at a designated wavelength into/from a common input/output (I/O) optical fiber.

**[0005]** The ever-increasing demands for greater bandwidth are driving the telecommunications industry toward greater number of wavelength channels. Adding to this trend, the dimensions of the optical transceivers are decreasing dramatically, requiring increasingly smaller micro-optical beam collimators and pitches between adjacent channels to keep the size of wave-division multiplexing (WDM) devices as

small as possible. Further, increasing demands for greater device reliability calls for the use of fabrication techniques that keep the optical components in the WDM device in relative alignment. In addition, the micro-optical beam collimators occupy significant space in WDM and largely define the device form factor while also playing a key role in device reliability and optical performance.

**[0006]** In this regard, **FIG. 1** is a perspective view of a collimator assembly array **100**. In particular, the collimator assembly array **100** includes a plurality of collimator assemblies **102(1)-102(3)** (referred to generally as collimator assembly **102**). Each collimator assembly **102** includes a collimator **104** and a wedge mount **106**. The wedge mount **106** includes a left wedge **108A** and a right wedge **108B**. Alignment and tuning of the collimator **104** is accomplished by translating and/or rotating the left wedge **108A** and right wedge **108B** relative to one another. For example, the left wedge **108A** and right wedge **108B** may be rotated in opposite directions to alter the vertical alignment of the collimator **104**. The wedge mount **106** provides flexibility in assembly of passive optical sub-assembly (POSA) and other optical assemblies, but limits the minimum width (P1) between adjacent collimators **104** in the collimator assembly array **100** and the minimum height (H1) of the array. For example, the wedge mount **106** creates a gap (H2) between a substrate **110** and a bottom of the collimator **102**. Accordingly, the wedge mounts **106** and other similar mounts limit collimator density.

**[0007]** No admission is made that any reference cited herein constitutes prior art. Applicant expressly reserves the right to challenge the accuracy and pertinency of any cited documents.

## SUMMARY

**[0008]** The disclosure relates generally to micro-optical systems, and particularly relates to tuned high-density collimators and methods for tuning. One embodiment of the disclosure relates to a tuned collimator comprising a mount, a collimating lens, and a pigtail. The mount defines a vertical y-axis. The collimating lens is secured to the mount. The collimating lens includes a first interface and defines a first central axis. The pigtail includes a ferrule secured to the mount and an optical fiber having a portion positioned within the ferrule. The ferrule defines a second central axis aligned with the

first central axis of the collimating lens along a z-axis perpendicular to the y-axis. The optical fiber includes an end face at least partially defining a second interface. The collimating lens and the pigtail form an optical light path from the end face of the optical fiber through the collimating lens. The first interface of the collimating lens and/or the second interface of the pigtail is planar and non-perpendicular to the z-axis. The collimating lens and the pigtail are rotationally oriented around the z-axis relative to each other such that a light pointing angle of the optical light path within the collimating lens is perpendicular to the y-axis. In other words, axial rotation of the ferrule relative to the collimating lens vertically aligns the optical light path within the collimating lens. Vertical alignment of the optical light path by rotation of the ferrule allows for collimator tuning without wedge mounts or other similar mounts, thereby allowing for a higher-density and lower profile configuration.

**[0009]** One embodiment of the disclosure relates to a tuned collimator comprising a mount, a collimating lens, and a pigtail. The mount has a top and a bottom and defines a vertical y-axis extending therebetween. The bottom of the mount is configured to be secured to a substrate. The collimating lens is secured to the mount. The collimating lens has a first front surface and a first back surface and defines a first central axis extending therebetween. The first back surface at least partially defines a first interface. The pigtail includes a ferrule secured to the mount and an optical fiber having a portion positioned within the ferrule. The ferrule has a second front surface and a second back surface and defines a second central axis extending therebetween. The second central axis of the ferrule is aligned with the first central axis of the collimating lens along a z-axis perpendicular to the y-axis. The optical fiber includes an end face at least partially defining a second interface. The collimating lens and the pigtail form an optical light path from the end face of the optical fiber through the first back surface and the first front surface of the collimating lens. At least one of the first interface of the collimating lens or the second interface of the pigtail is planar and non-perpendicular to the z-axis. The collimating lens and the pigtail are rotationally oriented around the z-axis relative to each other such that a light pointing angle of the optical light path within the collimating lens is perpendicular to the y-axis.

**[0010]** A further embodiment includes a method for tuning a collimator. The method includes positioning a collimating lens to a mount of a collimator. The collimating lens has a first front surface and a second back surface and defines a first central axis extending therebetween. The mount has a top and a bottom and defines a vertical y-axis extending therebetween. The method further includes aligning a second central axis of a ferrule of a pigtail with the first central axis of the collimating lens along a z-axis perpendicular to the vertical y-axis. The ferrule has a second front surface and a second back surface and a second central axis extending therebetween. The method further includes rotating at least one of the pigtail or the collimating lens about the z-axis relative to each other to change a light pointing angle of an optical light path within the collimating lens from being non-perpendicular to the y-axis to being perpendicular to the y-axis. The optical light path extends from an end face of an optical fiber of the pigtail through the first back surface and the first front surface of the collimating lens. The optical fiber having a portion is positioned within the ferrule.

**[0011]** Additional features and advantages will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the embodiments as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

**[0012]** It is to be understood that both the foregoing general description and the following detailed description are merely exemplary, and are intended to provide an overview or framework to understanding the nature and character of the claims. The accompanying drawings are included to provide a further understanding, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiments, and together with the description serve to explain principles and operation of the various embodiments.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0013]** **FIG. 1** is a perspective view of a collimator assembly array including wedge mounts.

**[0014]** **FIG. 2A** is a perspective view of a square tube collimator.

**[0015]** **FIG. 2B** is a top view of the square tube collimator of **FIG. 2A**.

**[0016]** **FIG. 3A** is a front view of a square tube collimator array of a plurality of the square tube collimators of **FIGS. 2A-2B**.

**[0017]** **FIG. 3B** is a top view of a micro-optical assembly including the square tube collimator arrays of **FIG. 3A.**

**[0018]** **FIG. 4A** is a top view of an aligned pigtail and a collimating lens with ideal cuts and alignment.

**[0019]** **FIG. 4B** is a top view of the aligned pigtail and collimating lens of **FIG. 4A** illustrating an optical light path therethrough.

**[0020]** **FIG. 4C** is a side view of the pigtail and collimating lens of **FIG. 4B**.

**[0021]** **FIG. 4D** is a diagram illustrating orientation of the pigtail of **FIG. 4A**.

**[0022]** **FIG. 4E** is a diagram illustrating orientation of the collimating lens of **FIG. 4A**.

**[0023]** **FIG. 5A** is a top view of a pigtail and collimating lens with a vertically imperfect cut and/or alignment before tuning.

**[0024]** **FIG. 5B** is a top view of the aligned pigtail and collimating lens of **FIG. 5A** illustrating an optical light path therethrough.

**[0025]** **FIG. 5C** is a side view of the pigtail and collimating lens of **FIG. 5B**.

**[0026]** **FIG. 5D** is a diagram illustrating orientation of the pigtail of **FIG. 5A**.

**[0027]** **FIG. 5E** is a diagram illustrating orientation of the collimating lens of **FIG. 5A**.

**[0028]** **FIG. 6A** is a top view of a pigtail and collimating lens with a vertically imperfect cut and/or alignment after tuning.

**[0029]** **FIG. 6B** is a top view of the aligned pigtail and collimating lens of **FIG. 6A** illustrating an optical light path therethrough.

**[0030]** **FIG. 6C** is a side view of the pigtail and collimating lens of **FIG. 6B**.

**[0031]** **FIG. 6D** is a diagram illustrating orientation of the pigtail of **FIG. 6A**.

**[0032]** **FIG. 6E** is a diagram illustrating orientation of the collimating lens of **FIG. 6A**.

**[0033]** **FIG. 7A** is a top view of a pigtail and collimating lens with a laterally imperfect cut and/or alignment before tuning.

**[0034]** **FIG. 7B** is a top view of the aligned pigtail and collimating lens of **FIG. 7A** illustrating an optical light path therethrough.

**[0035]** **FIG. 7C** is a side view of the pigtail and collimating lens of **FIG. 7B**.

**[0036]** **FIG. 7D** is a diagram illustrating orientation of the pigtail of **FIG. 7A**.

**[0037]** **FIG. 7E** is a diagram illustrating orientation of the collimating lens of **FIG. 7A**.

**[0038]** **FIG. 8A** is a top view of a pigtail and collimating lens with a laterally imperfect cut and/or alignment after tuning.

**[0039]** **FIG. 8B** is a top view of the aligned pigtail and collimating lens of **FIG. 8A** illustrating an optical light path therethrough.

**[0040]** **FIG. 8C** is a side view of the pigtail and collimating lens of **FIG. 8B**.

**[0041]** **FIG. 8D** is a diagram illustrating orientation of the pigtail of **FIG. 8A**.

**[0042]** **FIG. 8E** is a diagram illustrating orientation of the collimating lens of **FIG. 8A**.

**[0043]** **FIG. 9** is a front view of a triangular tube collimator array.

**[0044]** **FIG. 10** is a front view of a hexagonal tube collimator array.

**[0045]** **FIG. 11A** is a side view of a v-groove collimator.

**[0046]** **FIG. 11B** is a front view of the v-groove collimator of **FIG. 11A**.

**[0047]** **FIG. 12** is a flowchart illustrating processing steps for tuning a collimator.

## DETAILED DESCRIPTION

**[0048]** Reference will now be made in detail to the present preferred embodiments, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. Cartesian coordinates are provided in some of the drawings for the sake of reference and for ease of discussion and are not intended to be limiting as to direction and orientation.

**[0049]** The terms “left,” “right,” “top,” “bottom,” “front,” “back,” “horizontal,” “parallel,” “perpendicular,” “vertical,” “lateral,” “coplanar,” and similar terms are used for convenience of describing the attached figures and are not intended to limit this description. For example, the terms “left side” and “right side” are used with specific

reference to the drawings as illustrated and the embodiments may be in other orientations in use. Further, as used herein, the terms "horizontal," "parallel," "perpendicular," "vertical," "lateral," etc., include slight variations that may be present in working examples.

**[0050]** The disclosure relates generally to micro-optical systems, and particularly relates to tuned high-density collimators and methods for tuning. One embodiment of the disclosure relates to a tuned collimator comprising a mount, a collimating lens, and a pigtail. The mount defines a vertical y-axis. The collimating lens is secured to the mount. The collimating lens includes a first interface and defines a first central axis. The pigtail includes a ferrule secured to the mount and an optical fiber having a portion positioned within the ferrule. The ferrule defines a second central axis aligned with the first central axis of the collimating lens along a z-axis perpendicular to the y-axis. The optical fiber includes an end face at least partially defining a second interface. The collimating lens and the pigtail form an optical light path from the end face of the optical fiber through the collimating lens. The first interface of the collimating lens and/or the second interface of the pigtail is planar and non-perpendicular to the z-axis. The collimating lens and the pigtail are rotationally oriented around the z-axis relative to each other such that a light pointing angle of the optical light path within the collimating lens is perpendicular to the y-axis. In other words, axial rotation of the ferrule relative to the collimating lens vertically aligns the optical light path within the collimating lens. Vertical alignment of the optical light path by rotation of the ferrule allows for collimator tuning without wedge mounts or other similar mounts, thereby allowing for a higher-density and lower profile configuration.

**[0051]** **FIGS. 2A-2B** are views of a square tube collimator **200** (also referred to as a micro-optical system). In particular, **FIG. 2A** is a perspective view of a square tube collimator **200**, and **FIG. 2B** is a top view of the square tube collimator **200** of **FIG. 2A**. The tuned collimator (embodied as a square tube collimator **200**) includes a mount (embodied as glass tube **202**), a collimating lens **204**, and a pigtail **206**. The mount **202** defines a vertical y-axis. The collimating lens **204** is secured to the mount **202**. The collimating lens **204** includes a first interface **208** (**FIG. 2B**) and defines a first central axis A1 (not shown but coaxial with the z-axis). The pigtail **206** includes a ferrule **210**

secured to the mount **202** and an optical fiber **212** having a portion positioned within the ferrule **210**. The ferrule **210** defines a second central axis A2 (not shown but coaxial with the z-axis) aligned with the first central axis A1 of the collimating lens **204** along a z-axis perpendicular to the y-axis. The optical fiber **212** includes an end face **214** at least partially defining a second interface **216**. The collimating lens **204** and the pigtail **206** form an optical light path from the end face **214** of the optical fiber **212** through the collimating lens **204**. The first interface **208** (**FIG. 2B**) of the collimating lens **204** and/or the second interface **216** (**FIG. 2B**) of the pigtail **206** is planar and non-perpendicular to the z-axis. The collimating lens **204** and the pigtail **206** are rotationally oriented around the z-axis relative to each other such that a light pointing angle of the optical light path within the collimating lens **204** (and exiting the collimating lens **204**) is perpendicular to the y-axis. In other words, axial rotation of the pigtail **206** relative to the collimating lens vertically aligns the optical light path within the collimating lens **204**. Vertical alignment of the optical light path by rotation of the pigtail **206** allows for collimator tuning without wedge mounts **106** (see **FIG. 1**) or other similar mounts, thereby allowing for a higher-density and lower profile configurations.

**[0052]** It is noted that the light pointing angle within the collimating lens **204** is in the range of 0 to 0.2 degrees, and in particular, between 0.01 and 0.1 degrees. The light pointing angle achieved by the high-density tuned collimator **200** of the present disclosure is far more accurate than other collimators which could only achieve a light pointing angle greater than 0.2 degrees, and in particular, about 0.5 degrees.

**[0053]** The high-density tuned collimator **200** (such as a square tube collimator and/or v-groove collimator) increase channel density (also referred to as port density). See U.S. Provisional Patent Application No. 62/423,364 and U.S. Patent Application No. 15/422,705, entitled "Micro-Optical Systems and Assemblies using Glass Tubes and Methods of Forming Same," which are incorporated herein by reference in their entireties. Accordingly, the increased port density and more compact form factor increases the signal transport channels within a given space, which in turn provides higher signal transport speed and broad bandwidth. Such collimators may be used in constructing a Receiver Optical Sub-Assembly (ROSA) and/or a Transmitter Optical Sub-Assembly (TOSA), such as in a passive optical sub-assembly (POSA) within a

transceiver. The utilization of square glass tube **202** and/or V-groove in the assembly of collimators reduces the packing density of collimators in the device, thereby reducing the POSA form factor.

**[0054]** The glass tube **202** (e.g., cylindrical) has a front end **218A,** a back end **218B** (opposite the front end **218A**), a left side **220A**, and a right side **220B** (opposite the left side **220A**) a top side **222A**, and a bottom side **222B** (opposite the top side **222A**). In particular, the glass tube **202** defines an x-axis that extends between and through the left side **220A** and the right side **220B**, a y-axis that extends between and through the top side **222A** and the bottom side **222B**, and a z-axis that extends between and through the front end **218A** and the back end **218B**. It is noted that the bottom side **222B** may be mounted to a substrate. As used herein, the term "cylindrical" is used in its most general sense and can be defined as a three-dimensional object formed by taking a two-dimensional object and projecting it in a direction perpendicular to its surface. Thus, a cylinder, as the term is used herein, is not limited to having a circular cross-section shape but can have any cross-sectional shape, such as the square cross-sectional shape, triangular cross-sectional shape, hexagonal cross-sectional shape, etc.

**[0055]** The glass tube **202** includes a body **224** defining a central bore **226**. In particular, the body **224** includes an inner surface **227** defining the central bore **226** with a round cross-sectional shape (although other cross-sectional shapes may be used) and an outer surface **228** defining a square cross-sectional shape (although other cross-sectional shapes may be used). In particular, the outer surface **228,** including the left side **220A**, right side **220B**, top side **222A**, and bottom side **222B,** are each flat, perpendicularly oriented to form a square shape. The square cross-sectional shape provides for high-density, ease of manufacturability, and ease of assembly to a substrate, among other advantages. In certain embodiments, the bore **226** is centered within the body **224** of the glass tube **202** so that the central bore **226** is co-axial with the body **224** along central tube axis AT (not shown but coaxial with the z-axis). In other embodiments, it may be desirable to have the bore **226** off-center relative to a central axis of the body **224**.

**[0056]** The glass tube **202** has an axial length L in the z-direction and widths WX and WY in the x-direction and y-direction, respectively. In certain embodiments, the length L is from 1 mm to 20 mm, or between 5 mm and 20 mm, or between 5 mm and 10 mm. In

certain embodiments, WX and WY have a maximum dimension, or width, measured in a plane that is perpendicular to the tube central axis AT, that is in the range from about 0.1 mm to about 20 mm, or in the range from about 0.1 mm to about 10 mm, or in the range from about 0.125 mm to about 5 mm, or in the range from about 0.125 mm to about 2 mm. The central bore **226** has a diameter DB in the range from 50 microns to 1 cm, or more preferably 125 microns to 1.8 mm. In an example where the widths WX = WY = W, the diameter DB can be in the range $(0.3)W \leq DB \leq (0.8)W$.

**[0057]** The square tube collimator **200** further includes optical elements, such as the collimating lens **204** (also referred to as a c-lens), ferrule **210**, etc., which can be secured to the glass tube **202** using a securing mechanism (e.g., an adhesive). The collimating lens **204** has a front surface **230A** and a back surface **230B** opposite thereto, and defines an optical axis OA (not shown but coaxial with the z-axis). In the example shown, the front surface **230A** is convex while the back surface **230B** is planar and angled (also referred to as tilted), such as in the x-z plane. However, in other embodiments the front surface **230A** is planar. It is noted that the back surface **230B** of the collimator **200** at least partially defines the first interface **208**. In certain embodiments, the front surface **230A** of collimating lens **204** can reside or protrude outside of the central bore **226**. In other words, a front-end portion of the collimating lens **204** can extend slightly past the front end **218A** of the glass tube **202**. In certain embodiments, the collimating lens **204** can be formed as a gradient-index (GRIN) element that has a planar front surface **230A**. The collimating lens **204** can consist of a single lens element while in another example it can consist of multiple lens elements. In the discussion below, the collimating lens **204** is shown as a single lens element for ease of illustration and discussion.

**[0058]** The ferrule **210** provides optical fiber support. The ferrule **210** includes a central bore **232** that runs between a front end and a back end along a ferrule central axis AF (not shown but coaxial with the z-axis), which in an example is co-axial with the tube central axis AT of the glass tube **202** and the optical axis OA of the collimating lens **204**. The central bore **226** can include a flared portion **234** at the back end of the ferrule **210**. The ferrule **210** includes a front surface **236A** and a back surface **236B** (opposite the front surface **236A**).

**[0059]** An optical fiber **212** has a coated portion **238** and an end portion **240**. The end portion **240** is bare glass (e.g., is stripped of the coated portion **238**) and is thus referred to as the "bare glass portion." The bare glass portion **240** includes the polished end face **214** that defines a proximal end of the optical fiber **212**. The bare glass portion **240** of the optical fiber **212** extends into the central bore **232** of the ferrule **210** at the back end of the ferrule **210**.

**[0060]** The fiber optic pigtail **206** includes the ferrule **210**, optical fiber **212**, and securing element **244**. In this way, the fiber optic pigtail **206** resides at least partially within the bore **226** adjacent the back end **218B** of the glass tube **202**. The securing element **244** (e.g., adhesive, a mechanical fastener, etc.) can be disposed around the optical fiber **212** at the back end of the ferrule **210** to secure the optical fiber **212** to the ferrule **210**. The front surface **236A** of the ferrule **210** and/or the end face **214** of the optical fiber **212** are planar and angled in the x-z plane (around the y-axis). In particular, the front surface **236A** of the ferrule **210** and the end face **214** of the optical fiber **212** may be coplanar, and in certain embodiments, may be coplanar within 200 nm of each other, and in particular within 100 nm of each other. Further, the front surface **236A** and/or end face **214** are axially spaced apart from the angled back surface **230B** of the collimating lens **204** to define a gap **246** that has a corresponding axial gap distance DG.

**[0061]** The square tube collimator **200** includes the glass tube **202**, the collimating lens **204**, and the fiber optic pigtail **206**. The glass tube **202** serves in one capacity as a small lens barrel that supports and protects the collimating lens **204** and the fiber optic pigtail **206**, particularly the bare glass portion **240** and its polished end face **214**. The glass tube **202** also serves in another capacity as a mount or mounting member that allows for the square tube collimator **200** to be mounted to a support substrate. In this capacity, at least one flat surface (e.g., bottom side **222B**) serves as a precision mounting surface. In an example, the glass tube **202**, the collimating lens **204,** and the ferrule **210** are all made of a glass material, and further in an example, are all made of the same glass material. Making the glass tube **202**, the collimating lens **204** and the ferrule **210** out of a glass material has the benefit that these components will have very close if not identical coefficients of thermal expansion (CTE). This feature is particular advantageous in environments that can experience large swings in temperature.

**[0062]** In an example, the optical elements used in micro-optical systems are sized to be slightly smaller than the diameter of the bore **226** (e.g., by a few microns or tens of microns) so that the optical elements can be inserted into the bore **226** and be movable within the bore **226** to a select location. In an example, the select location is an axial position where optical element resides for the micro-optical system to have optimum or substantially optimum optical performance. Here, substantially optimum performance means performance that may not be optimum but that is within a performance or specification for the micro-optical system. In another example, the optical elements have a clearance with respect to the bore **226** in the range of a few microns (e.g., 2 microns or 3 microns) to tens of microns (e.g., 20 microns up to 50 microns). A relatively small value for the clearance allows for the optical elements **110** to be well-aligned with a central bore axis AB (not shown but coaxial with the z-axis), e.g., to within a few microns (e.g., from 2 microns to 5 microns).

**[0063]** The optical elements and the support/positioning elements can be inserted into and moved within bore **226** to their select locations using micro-positioning devices. The optical elements and the support/positioning elements can be secured within the bore **226** using a number of securing techniques. One example securing technique uses a securing feature that is an adhesive (e.g., a curable epoxy). Another securing technique uses a securing feature that involves a glass soldering to create one or more glass solder points. Another securing technique uses glass welding to create a securing feature in the form of one or more glass welding points. A combination of these securing features can also be employed. Thus, one or more optical elements can be secured within the bore **226** using a securing feature and can also be supported and/or positioned using one or more support/positioning elements. The non-adhesive securing techniques allow for the micro-optical systems disclosed herein to remain free of adhesives so that, for example, micro-optical systems can consist of glass only.

**[0064]** **FIG. 3A** is a front view of a square tube collimator array **300** of a plurality of the square tube collimators **200(1)-200(3)** of **FIGS. 2A-2B**. The square tube collimators **200(1)-200(3)** (referred to generally as square tube collimator **200**) provide high density, and in particular, a higher density than the collimator array **100** using the wedge mounts **106** of **FIG. 1**. In other words, the tuned collimators (or micro-optical systems) disclosed

form square tube collimator arrays **300** (or micro-optical assemblies) that require a small form factor.

**[0065]** The array **300** has a pitch P2 in the x-direction (e.g., of approximately p = WX). In certain embodiments, the pitch P2 is about 2 mm or between 0.1 mm to 10 mm, which is less than the P1 of the collimator array **100** of **FIG. 1**. The ability to form compact arrays **300** of micro-collimators **200** is advantageous considering that some complex wave division multiplexing (WDM) micro-optical assemblies can have tens or even hundreds of channels. Further, the array **300** has a minimized height compared to the collimator array **100** of **FIG. 1**.

**[0066]** The one or more flat sides **214A-216B** of glass tubes **202** also provide an advantage in configuring the array **300** by being able to place sides of adjacent collimators **200** in close proximity to one another and secure them to each other as well as to an upper surface of a support substrate **302**. Once a first collimator **200** is properly aligned on the support substrate **302** (e.g., relative to a reference or alignment feature thereon), then the other collimators **200** can be added immediately adjacent the first aligned collimator **200**. As explained in more detail below, each collimator **200** may be individually tuned.

**[0067]** After alignment, the array **300** of collimators **200** can be held together by an adhesive (e.g., a UV curable adhesive) that wicks into gaps **303** between adjacent glass tubes **202**. In an example, the adhesive can then be activated by UV light. The collimators **200** can also be formed as a stand-alone array **300** and then attached to an upper surface of a support substrate **302**. The collimators **200** that make up the array **300** can also be secured to one another using at least one of the laser welding process and the glass soldering process as described above to form an adhesive-free array **300**. A gap is shown between adjacent collimators **200** in **FIG. 3A** for ease of illustration and, in practice, the adjacent collimators **200** may be much closer to each other with space provided for, for example, an adhesive, or may be in contact with each other.

**[0068]** **FIG. 3B** is a top view of a micro-optical assembly **304** including the square tube collimator arrays **300** of **FIG. 3A.** Once again, a gap is shown between adjacent collimators **200(1)**, **200(3)**, and collimators **200(2)**, **200(4)** for ease of illustration and, in practice, the adjacent collimators **200(1)**, **200(3)**, and **200(2)**, **200(4)** may be much closer

to each other with space provided for, for example, an adhesive, or may be in contact with each other. In general, the micro-optical assembly **304** comprises at least one collimator **200** supported on an upper surface **306** of the support substrate **302**. In an example, the micro-optical assembly **304** can include a housing **308** that defines a WDM module. In an example, the WDM module can have a small form factor as defined by length (e.g., in the range of 30mm to 41 mm), width (e.g., in the range of 14 mm to 28 mm), and height (within the range of 5 mm to 6 mm).

**[0069]** The particular example of micro-optical assembly **304** is in the form of a four-channel WDM device that employs five of the micro-collimators **200** disclosed herein and so is referred to hereinafter as the WDM micro-optical assembly **304**. It is noted that a more basic WDM micro-optical assembly **304** can employ only three micro-collimators **200** and is used to separate or combine two wavelengths. Likewise, more complicated WDM micro-optical assemblies **304** can employ many more micro-collimators **200** to separate or combine many more wavelengths besides two wavelengths or even four wavelengths (e.g., tens or even hundreds of different wavelengths). In examples, the WDM channels can be dense WDM (DWDM) channels or coarse WDM (CWDM) channels. Other types of micro-optical assemblies **304** besides the WDM micro-optical assembly described herein can also be formed using the basic techniques described herein. For example, the micro-optical assembly **304** can be used to form many types of free-space optical fiber devices, as well as compact variable optical attenuators, switches, optical amplifiers, taps, optical couplers/splitters, optical circulators, optical isolators, optical time-domain reflectometer (OTDRs), etc.

**[0070]** In an example, the support substrate **302** is made of glass (e.g., quartz) or sapphire. In another example, the support substrate **302** is made of a glass that is receptive to the formation of glass bumps. In other examples, the support substrate **302** can be made of stainless steel or silicon, a low-CTE metal alloy (e.g., having a CTE of < 10 ppm/°C, or more preferably CTE < 5 ppm/°C, or even more preferably CTE < 1 ppm/°C). Examples of metal alloys having such a low CTE include the nickel-iron alloy 64FeNi also known in the art under the registered trademarked INVAR® alloy or the nickel-cobalt ferrous alloy known in the art under the registered trademark KOVAR® alloy. In an example, the upper surface **306** is precision polished to be flat to within a

tolerance of 0.005 mm so that the collimators **200** can be precision mounted to the upper surface using the bottom side **216B**. As discussed above, the bottom side **216B** can be processed (e.g., polished, including laser performing laser polishing) to a tolerance similar to that of the upper surface **306** of the support substrate **302**. In an example, the support substrate **302** includes one or more reference features, such as alignment fiducials, for positioning and/or aligning the micro-collimators **200** and other optical components (e.g., optical filters, other micro-collimators, etc.).

**[0071]** The micro-collimators **200** are individually denoted **200P** and **200(1), 200(2), 200(3),** and **200(4)** and are arranged as shown in **FIG. 3B**. The micro-collimator **200P** serves as an input/output (I/O) port for a multi-wavelength light **310** having wavelengths $\lambda_1$ to $\lambda_4$ while the micro-collimators **200(1)-200(4)** (referred to generally as micro-collimators **200**) serve as the four individual channel ports. The I/O micro-collimator **200P** and the first micro-collimator **200(1)** are disposed facing each other along a first axis. The micro-optical assembly **304** also includes four optical filters **312(1)-312(4)** (referred to generally as optical filters **312**) operably arranged relative to the collimators **200** and respectively configured to transmit wavelengths $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$ and reflect the other wavelengths. The first optical filter **312(1)** is disposed between the I/O micro-collimator **200P** and the first micro-collimator **200(1)** and defines a second axis along which is disposed the second optical filter **312(2)** and the second micro-collimator **200(2)**. The second optical filter **312(2)** defines a third axis along which is disposed the third optical filter **312(3)** and the third micro-collimator **200(3)**. The third optical filter **312(3)** defines a fourth axis along which is disposed the fourth optical filter **312(4)** and the fourth micro-collimator **200(4)**.

**[0072]** In the DeMux operation, the multi-wavelength light **310** exits the I/O micro-collimator **200P** that defines the I/O port and travels towards the first optical filter **312(1)**. The first optical filter **312(1)** transmits the wavelength $\lambda_1$ to the first micro-collimator **200(1)** along the first axis and reflects the remaining wavelengths $\lambda_2$, $\lambda_3$, and $\lambda_4$ of multi-wavelength light **310** along the second axis. This reflected multi-wavelength light **310** is then incident upon the second optical filter **312(2)**, which transmits the wavelength $\lambda_2$ to the second micro-collimator **200(2)** and reflects the remaining wavelengths $\lambda_3$ and $\lambda_4$ of multi-wavelength light **310** along the third axis. This process is repeated for the

remaining two optical filters **312(3)** and **312(4)** and micro-collimators **200(3)** and **200(4)** along the third and fourth axes so that the wavelength components $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$ of the multi-wavelength light **310** are distributed to their respective collimators **200(1)-200(4)**. In the DeMux operation, the direction of the light 310 is reversed and the individual wavelengths $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$ from the individual micro-collimators **200(1)-200(4)** are recombined by the optical filters **312(1)-312(4)** into I/O micro-collimator **200P**.

**[0073]** The dimensions WX, WY and DB of the glass tubes **202** of the micro-collimators **200** may facilitate determination of the position of each wavelength channel on the support substrate **302**. The precision fabrication of the glass tubes **202** for the collimators **200** provides several advantages when fabricating optical assemblies such as the WDM micro-optical assembly described herein. For example, the distance between the bottom side **216B** and axis of the bore **226** can be selected to define a precise height and in-plane positioning of the optical axis and of the Gaussian optical beam associated with the given micro-collimator **200**.

**[0074]** The transparent nature of the glass tube **202** facilitates machine-vision-based assembly of the micro-optical assembly **304**, such as by being able to view one or more reference features (e.g., alignment fiducials) on the substrate **302** through the glass tube **202**. The transparent nature of the glass tube **202** also allows for visual inspection of the optical elements and support/positioning elements supported within the bore **226** of the glass tube **202** for reliability (e.g., inspecting the adhesive or securing features) or to control the gap distance between adjacent optical elements or the support/positioning elements by direct observation of the gap during assembly. In an example, the micro-collimators **200** and optical filters **312** can be secured to the upper surface **306** of the glass support substrate **302** using an adhesive, glass soldering or glass welding using a laser. A combination of these different securing techniques can also be employed. In an example, no adhesive is used in securing the collimators **200** and optical filters **312** to the upper surface **306** of the support substrate **302**. A no-adhesive embodiment of the micro-optical assembly **304** may be preferred in cases where uncertainty in the reliability of the adhesive is a concern.

**[0075]** **FIGS. 4A-4E** are views illustrating alignment of a pigtail **206(1)** and collimating lens **204(1)**. In particular, **FIG. 4A** is a top view of an aligned pigtail **206(1)**

and a collimating lens **204(1)** with ideal cuts and alignment. In this ideal situation, the first interface **208(1)** of the collimating lens **204(1)** and the second interface **216(1)** of the pigtail **206(1)** are parallel to each other with the same tilted angles α. Both of the pigtail **206(1)** and collimating lens **204(1)** may be manufactured to have a tilted angle (e.g., eight degree) to reduce induced return signals. In particular, when emitting a light signal from the pigtail **206(1)** to the collimating lens **204(1)**, the pigtail **206(1)** includes an incident angle $\Theta_{IN\ 1}$ and a refraction angle $\Theta_{OUT\ 1}$ and the collimating lens **204(1)** includes an incident angle $\Theta_{IN\ 2}$ and a refraction angel $\Theta_{OUT\ 1}$.

**[0076]** As illustrated, $\hat{k}_0$ is the unit vector representing the transfer direction of light within the pigtail, $\hat{k}_1$ is the unit vector representing the transfer direction of light within the air gap between the pigtail and the collimating lens, and $\hat{k}_2$ is the unit vector representing the transfer direction of light within the collimating lens **204(1)**. The unit vector $\hat{k}_2$ includes a light pointing angle (also referred to as a beam pointing angle) relative to the z-axis within the collimating lens **204(1)**. The indices of refraction of both glass components of pigtail **242(1)** and collimating lens **204(1)** are written as **n**. The normal direction of the first interface of the first glass component of the pigtail **206(1)** is $\hat{s}_1$, and the normal direction of the second interface of the collimating lens **204(1)** is $\hat{s}_2$. As explained in more detail below, the collimator **200** is tuned to ensure the light pointing angle of $\hat{k}_2$ is within the x-z plane (also referred to as the substrate plane) or without y component $|\hat{k}_2|_y = 0$. For simplicity, the axis direction of the pigtail (or the direction of the incoming light) is along the z-axis such that $\hat{k}_0 = \hat{z}$.

**[0077]** It is noted that the travel of optical light across different media interface obeys Snell's law as in **Equation 1** below in which $n_{in}$ and $n_{out}$ are the media index of refraction on the sides of the interface, $\theta_{in}$ and $\theta_{out}$ are the incident angle and the reflected angle respectively.

$$n_{in} \sin\theta_{in} = n_{out} \sin\theta_{out}$$

**Equation 1**

**[0078]** The vector form of light refraction across an interface could be written as in **Equation 2** below, in which $n_{in}$ and $n_{out}$ are the media index of refraction on sides of the interface, $\theta_{in}$ and $\theta_{out}$ are the incident angle and the reflected angle respectively. $\hat{v}_{in}$ and $\hat{v}_{out}$ are light direction vector before and after refraction with interface normal vector $\hat{n}_{in-out}$.

$$\hat{v}_{out} = \left(\frac{n_{in}}{n_{out}}\right)\hat{v}_{in} + \left(-\frac{n_{in}}{n_{out}}\cos\theta_{in} + \cos\theta_{out}\right)\hat{n}_{in-out}$$

**Equation 2**

**[0079]** Applying **Equation 2** on the first and second interface of the collimator system with surface normal direction $\hat{s}_1$ and $\hat{s}_2$ produces:

$$\left|\hat{k}_0\right|_y = \left(\frac{1}{n}\right)\left|\hat{k}_1\right|_y + \left(-\frac{1}{n}\cos\theta_{out,1} + \cos\theta_{in,1}\right)\left|\hat{s}_1\right|_y$$

**Equation 3**

$$\left|\hat{k}_2\right|_y = \left(\frac{1}{n}\right)\left|\hat{k}_1\right|_y + \left(-\frac{1}{n}\cos\theta_{in,2} + \cos\theta_{out,2}\right)\left|\hat{s}_2\right|_y$$

**Equation 4**

**[0080]** The combination of **Equations 3** and **4** produces **Equation 5** below:

$$\left|\hat{k}_2\right|_y = = \left|\hat{k}_0\right|_y - \left(-\frac{1}{n}\cos\theta_{out,1} + \cos\theta_{in,1}\right)\left|\hat{s}_1\right|_y + \left(-\frac{1}{n}\cos\theta_{in,2} + \cos\theta_{out,2}\right)\left|\hat{s}_2\right|_y$$

**Equation 5**

**[0081]** With constant $C_1 = -\frac{1}{n}\cos\theta_{out,1} + \cos\theta_{in,1}$ and $C_2 = -\frac{1}{n}\cos\theta_{in,2} + \cos\theta_{out,2}$ being positive, this equation indicates how the outgoing light pointing angle $\left|\hat{k}_2\right|_y$ changes with the pointing angle of the incoming light $\left|\hat{k}_0\right|_y$, and the normal direction of the tilted surfaces $\left|\hat{s}_1\right|_y$ and $\left|\hat{s}_2\right|_y$ in the x-z plane.

**[0082]** The incident angle $\Theta_{IN\ 2}$ from air gap **246** into the collimating lens **204(1)** is the same as the refraction angle $\Theta_{OUT\ 1}$ from pigtail **206(1)** into the air gap **246**. The

pointing angle or pointing direction of the light within the collimating lens $\hat{k}_2$ is the same as the original light direction $\hat{k}_0$. As long as the direction of light inside the pigtail $\hat{k}_0$ is in plane of substrate (X-Z plane), the outgoing light $\hat{k}_2$ is in the plane of substrate without any pointing angle issue.

**[0083]** **FIGS. 4B-4C** illustrate an optical light path **400(1)** through the pigtail **206(1)** and collimating lens **204(1)**. The optical light path **400(1)** is perfectly aligned with no deviation in the x, y, or z direction. **FIG. 4D** is a diagram illustrating orientation of the pigtail of **FIG. 4A,** and **FIG. 4E** is a diagram illustrating orientation of the collimating lens of **FIG. 4A**. As shown, there is no misalignment of the pigtail **206(1)** or the collimating lens **204(1)**.

**[0084]** In certain embodiments, assembling the collimator **200(1)** includes sliding the collimating lens **204(1)** into the glass tube **202** (shown in **FIGS. 2A-2B**). Once secured within the glass tube **202**, the pigtail **206(1)** is slid into the glass tube **202** from the other side of the glass tube **202**. The angled back surface **230B** (shown in **FIGS. 2A-2B**) of the collimating lens **204(1)** is used as a reference to align the pigtail **206(1)** to ensure both the first interfaces **208(1)** of the collimating lens **204(1)** and the second interface **216(1)** of the pigtail **206(1)** are parallel with the air gap **246** in between. However, due to tolerance variations or other inaccuracies, the pigtail **206(1)** and/or collimating lens **204(1)** may not be perfectly cut and/or aligned. Such deviations require further tuning to compensate for these inaccuracies, as discussed in more detail below.

**[0085]** **FIGS. 5A-5E** are views of a pigtail **206(2)** and collimating lens **204(2)** with a vertically imperfect cut and/or alignment before tuning. In particular, **FIG. 5A** is a top view of a pigtail and collimating lens with a vertically imperfect cut and/or alignment before tuning. Oftentimes it is difficult to manufacture or/and position both collimating lens **204(2)** and pigtails **206(2)** inside the glass tube **202** accurately, which may lead to some imperfections either in sizes or tilted angles (e.g., due variation within tolerance range). This may lead to deviation of the beam direction, also referred to as pointing angle offset.

**[0086]** One such type of pointing angle offset, as shown in **FIG. 5A**, is rotational misalignment out of the x-z plane (around the y-axis) or vertical misalignment. For example, the collimating lens **204(2)** may be rotationally misaligned or have an imperfect

cut. As a result, the collimating lens **204(2)** may be rotationally misaligned within the glass tube **202** (shown in **FIGS. 2A-2B**) out of the x-z plane by an angle of $\Delta\varphi_c$ around the z-axis. Due to this rotational misalignment, the normal direction of the second air-glass interface $\hat{s}_2$ is changed by $\Delta\varphi_c$ around the z-axis, and has a non-zero vertical component out of the x-z plane. In this situation, since originally there is no y component of light vector in the air gap $|\hat{k}_1|_y = 0$, the light vector $\hat{k}_2$ pointing out of **x–z** plane per **Equation 5** above.

**[0087]** **FIGS. 5B-5C** illustrate an optical light path **400(2)** through the pigtail **206(2)** and collimating lens **204(2)**. The optical light path **400(2)** is misaligned with deviation in the y direction. **FIG. 5D** is a diagram illustrating orientation of the pigtail **206(2)** of **FIG. 5A**, and **FIG. 5E** is a diagram illustrating orientation of the collimating lens **204(2)** of **FIG. 5A**. As shown, there is no misalignment of the pigtail **206(2)**, but there is misalignment of the collimating lens **204(2)**. In particular, the collimating lens **204(2)** is rotationally misaligned about the z-axis.

**[0088]** **FIGS. 6A-6E** are views of a pigtail **206(2)** and collimating lens **204(2)** with a vertically imperfect cut and/or alignment after tuning. **FIG. 6A** is a top view of a pigtail **206(2)** and collimating lens **204(2)** with a vertically imperfect cut and/or alignment after tuning. As noted above, the square tube collimators **200** (shown in **FIGS. 2A-2B**) are devoid of the wedge mount **106** illustrated in **FIG. 1**, and thus require a different mechanism for controlling the beam pointing angle.

**[0089]** To tune the pointing direction of the outgoing light back into the x-z plane (to cancel its **y** component), the direction of the light vector $\hat{k}_1$ in the air gap **246** should be rotated (around the z-axis) in the reverse direction (similar to **Equation 4** above) as in **Equation 6** below.

$$|\hat{k}_1|_y = -(-\cos\theta_{in,2} + \mathrm{ncos}\,\theta_{out,2})\,|\hat{s}_2|_y$$

**Equation 6**

**[0090]** Rotational adjustment of light vector $\hat{k}_1$ requires a rotational change of surface normal $\hat{s}_1$ on the reverse direction as the $\hat{k}_1$ (see **Equation 3** above) as in **Equation 7** below.

$$|\hat{s}_1|_y = -|\hat{k}_1|_y/(-\cos\theta_{out,1} + n\cos\theta_{in,1})$$

**Equation 7**

**[0091]** To compensate the rotational misalignment of the collimating lens **204(2)** around the z-axis, the pigtail **206(2)** may be rotated around the z-axis in the same direction. Alternatively, when a beam profiler is used to monitor the pointing angle offset in the practice, a positive offset of the pointing angle in the y direction could be corrected by counter-clockwise rotating the collimating lens **204(2)** and/or clockwise rotating the pigtail **206(2)** about the z-axis, such as when facing the front (with the collimating lens **204(2)** in front of the pigtail **206(2)**). In the same manner, the negative offset of the pointing angle in the y direction could be corrected by clockwise rotating the collimating lens **204(2)** and/or counter-clockwise rotating the pigtail **206(2)** (as per **Equation 5** above).

**[0092]** Rotating only the collimating lens **204(2)** or the pigtail **206(2)** may provide an upward limit on altering the y component of $|\hat{k}_2|_y$ (see **Equation 5** above) as in **Equation 8** below.

$$|\hat{k}_2|_{y,max} = 2\left(-\frac{1}{n}\cos\theta_{out,1} + \cos\theta_{in,1}\right)$$

**Equation 8**

**[0093]** For example, at standard tilted angle of $\alpha = 8°$ and with glass material index of refraction n = 1.75, the $|\hat{k}_2|_{y,max} = 0.87$. Any observed pointing angle offset values in **Y** component beyond this boundary would require tuning of the light propagation direction $\hat{k}_0$ within the pigtail **206(2)** simultaneously with the collimating lens **204(2)**.

**[0094]** **FIGS. 6B-6C** illustrate an optical light path **400(2)'** through the pigtail **206(1)** and collimating lens **204(2)**. The optical light path **400(2)'** is aligned without any deviation in the y direction. **FIG. 6D** is a diagram illustrating orientation of the pigtail **206(2)** of **FIG. 6A**, and **FIG. 6E** is a diagram illustrating orientation of the collimating lens **204(2)** of **FIG. 6A**. As shown, the pigtail **206(2)** has been rotated to adjust

alignment relative to the collimating lens **204(2)**. Accordingly, there is no misalignment of the pigtail **206(2)** in the x, y, or z direction. In other words, the light pointing angle $\hat{k}_2$ is within the x-z plane or without y component $|\hat{k}_2|_y = 0$.

**[0095]** This methodology applies to cases of inaccurate pointing of the collimating lens **204(2)** and/or the pigtail **206(2)** in the orientation around the z-axis due to assembly or size inaccuracies, inaccurate cut of the angled surface of the collimating lens **204(2)** and/or pigtail **206(2)** out of the x-z plane, fiber off center of the collimator **200** out of the x-z plane, or any combination thereof.

**[0096]** **FIGS. 7A-7E** are views of a pigtail and collimator lens with a laterally imperfect cut and/or alignment before tuning. In particular, **FIG. 7A** is a top view of a pigtail and collimating lens with a laterally imperfect cut and/or alignment before tuning. Oftentimes it is difficult to manufacture or/and position both collimating lens **204(2)** and pigtails **206(2)** inside the glass tube **202** accurately, which may lead to some imperfections either in sizes or tilted angles (e.g., due variation within tolerance range). This may lead to deviation of the beam direction, also referred to as pointing angle offset.

**[0097]** Another type of pointing angle offset, as shown in **FIG. 7A**, is rotational misalignment within the x-z plane or horizontal misalignment. For example, the collimating lens **204(3)** may be rotationally misaligned in the x-z plane by an angle of $\Delta\theta$ around the y-axis. As a result, the normal direction of the second air-glass interface $\hat{s}_2$ is changed by $\Delta\theta$ (around the y-axis), but still in the x-z plane. As long as both the surface normal vectors $\hat{s}_1$ and $\hat{s}_2$ in the x-z plane without y components, the light vectors $\hat{k}_2$ remain in the x-z plane without y component as $\hat{k}_0$ (see **Equation 4** above).

**[0098]** **FIGS. 7B-7C** illustrate an optical light path **400(3)** through the pigtail **206(3)** and collimating lens **204(3)**. The optical light path **400(3)** is misaligned with deviation around the y-axis (within the x-z plane). **FIG. 7D** is a diagram illustrating orientation of the pigtail of **FIG. 7A**, and **FIG. 7E** is a diagram illustrating orientation of the collimating lens of **FIG. 7A**. As shown, there is no misalignment of the pigtail **206(3)**, but there is misalignment of the collimating lens **204(3)**. In particular, the collimating lens **204(3)** is rotationally misaligned about the y-axis.

**[0099]** **FIGS. 8A-8E** are views of a pigtail **206(3)** and collimating lens **204(3)** with a laterally imperfect cut and/or alignment after tuning. In particular, **FIG. 8A** is a top view

of a pigtail **206(3)** and collimating lens **204(3)** with a laterally imperfect cut and/or alignment after tuning. In such a circumstance, the collimator **200** is rotated about the y-axis to rotationally adjust the collimator **200** in the substrate plane x-z to compensate for the pointing angle offset. In this way, the collimator **200** is usually vertically aligned before the collimator is horizontally aligned, because rotating the pigtail **206(3)** and/or collimating lens **204(3)** about the z-axis may alter horizontal alignment (in the x-direction) of the light pointing angle as well as vertical alignment (in the y-direction) of the light pointing angle.

**[00100]** **FIG. 8B-8C** illustrate an optical light path **400(3)'** through the pigtail **206(3)** and collimating lens **204(3)**. The optical light path **400(3)'** is aligned without any deviation in the y direction. **FIG. 8D** is a diagram illustrating orientation of the pigtail of **FIG. 8A,** and **FIG. 8E** is a diagram illustrating orientation of the collimating lens of **FIG. 8A**. As shown, the pigtail **206(2)** and collimating lens **204(3)** have been rotated to adjust alignment relative to the collimating lens **204(3)**. Accordingly, there is no misalignment of the optical path within the collimating lens in the x, y, or z direction.

**[00101]** This methodology applies to cases of inaccurate pointing of the collimating lens **204(3)** and/or the pigtail **206(3)** in the orientation around the y-axis due to assembly or size inaccuracies, inaccurate cut of the angled surface of the collimating lens **204(3)** and/or pigtail **206(3)** in of the x-z plane, fiber off center of the collimator **200** out of the x-z plane, or any combination thereof.

**[00102]** It is noted that the collimator **200** discussed in **FIGS. 4A-8E** above may also be tuned by altering the gap distance DG. In other words, translating the pigtail **206** and/or collimating lens **204** toward or away from each other may alter the light pointing angle within the collimating lens **204**.

**[00103]** **FIG. 9** is a front view of a triangular tube collimator array **900**. The triangular tube collimator array **900** includes five collimators **902(1)-902(5)** (referred to generally as collimators **902**), although fewer or more collimators **902** may be used. The collimators **902** are the same as those discussed above with respect to **FIGS. 2A-3B** except where otherwise noted. Each collimator **902** includes a glass tube **202'** with a triangular cross-section. In this way, the first collimator **902(1),** third collimator **902(3)**, and fifth collimator **902(5)** are oriented in the same direction around the z-axis. The

second collimator **902(2)** and fourth collimator **902(4)** are oriented in the same direction as each other, but rotated about the z-axis. This minimizes the pitch between adjacent collimators **902**. Epoxy **904** secures the collimators **902** to the substrate **302** and to each other. It is anticipated that the collimators **902** are each individually tuned and aligned, and then the epoxy **904** is applied. In particular, the collimators **902** are tuned as described above with respect to **FIGS. 4A-8E**.

**[00104]** **FIG. 10** is a front view of a hexagonal tube collimator array **1000**. The hexagonal tube collimator array **1000** includes five collimators **1002(1)-1002(5)** (referred to generally as collimators **1002**), although fewer or more collimators **1002** may be used. The collimators **1002** are the same as those discussed above with respect to **FIGS. 2A-3B** except where otherwise noted. Each collimator **1002** includes a glass tube **202''** with a hexagonal cross-section. In this way, collimators **1002** may be stacked on top of one another. In other words, the first collimator **1002(1)** is stacked on top of and between the third collimator **1002(3)** and the fourth collimator **1002(4)**. Further, the substrate **302'** is grooved to receive the hexagonal collimators **1002** for ease of manufacture. Epoxy **1004** secures the collimators **1002** to the substrate **302'** and to each other. It is anticipated that the collimators **1002** are each individually tuned and aligned, and then the epoxy **1004** is applied. In particular, the collimators **1002** are tuned as described above with respect to **FIGS. 4A-8E**.

**[00105]** **FIG. 11A** is a side view of a v-groove collimator **1100**, and **FIG. 11B** is a front view of the v-groove collimator of **FIG. 11A**. The collimator **1100** is the same as those discussed above with respect to **FIGS. 2A-3B** except where otherwise noted. The collimators **1100** are tuned as described above with respect to **FIGS. 4A-8E**.

**[00106]** The collimator **1100** includes a collimating lens **204** (e.g., a glass or silica collimating lens), a fiber optic pigtail **206** and a groove **1104** (e.g., a generally V-shaped groove) formed in a mount **1102**. The collimating lens **204** and the fiber optic pigtail **206** are disposed in the groove **1104**. The collimating lens **204** is configured to receive a light signal provided to the WDM multiplexer/demultiplexer from an external optical transmission system or provide a light signal multiplexed or demultiplexed by the WDM to an external optical transmission system. The collimating lens **204**, for example, may be configured to receive a light signal from a fiber optic element for multiplexing or

demultiplexing and/or to provide a multiplexed or demultiplexed light signal to an external fiber optic element. The fiber optic pigtail **206** is optically coupled to the collimating lens **204** and is configured to provide a light signal to the collimating lens **204** from the external fiber optic element and/or to receive the light signal from the collimating lens **204** for transmission to the external fiber optic element.

**[00107]** In various embodiments, the collimating lens **204** and the fiber optic pigtail **206** may or may not contact each other. The collimating lens **204** and the fiber optic pigtail **206** may be securable to the groove **1104** independent of each other to allow for precise adjustment of a pointing angle between an optical beam from the collimator **1100** and a side and/or bottom surface of the groove. In addition, the collimating lens **204** and fiber optic pigtail **206** may have the same or different outer diameter.

**[00108]** The mount **1102** of the collimator **1100** has a top side **1106A** and a bottom side **1106B** (opposite the top side **1106A**). The bottom side **1106B** is generally flat for mounting on a substrate of a WDM multiplexer/demultiplexer or other optical system. The mount **1102** further includes a width that is less than a width of the collimating lens **204** and a width of the fiber optic pigtail **206**. The groove **1104** is in the top side **1106A** to hold the collimating lens **204** and fiber optic pigtail **206**.

**[00109]** The collimator **1100** can be tuned and altered according to the methodology discussed above with respect to **FIGS. 4A-8E**. Also, an additional adjustment freedom could be achieved by using a pigtail **206** and a collimating lens **204** with slightly different diameters. When the axis of the pigtail **206** is closer to the groove **1104** than the axis of the collimating lens **204**, the out-going beam tends to tilt away from the substrate x-z plane. When the axis of the pigtail **206** is farther away from the groove **1104** than the axis of the collimating lens **204**, the out-going beam tends to tilt closer toward the substrate plane. In this way, the v-groove collimator **1100** could be tuned in the direction normal to the substrate. The difference in distance for the collimating lens **204** and pigtail **206** to the groove **1104** could be controlled with different thickness of epoxy used to secure the collimating lens **204** and the pigtail **206** on the groove **1104**.

**[00110]** **FIG. 12** is a flowchart illustrating processing steps **1200** for tuning a collimator. As embodied herein and depicted in **FIG. 12**, step **1202** includes positioning a collimating lens **204** to a mount **202** of a collimator **200**. In particular, the collimating

lens **204** may be positioned within a glass tube **202** or on top of a v-groove mount **1102** (or other similar mount). Step **1204** includes aligning a second central axis of a ferrule **210** of a pigtail **206** with the first central axis of the collimating lens **204** along a z-axis perpendicular to the vertical y-axis. Step **1206** includes rotating at least one of the pigtail **206** or the collimating lens **204** about the z-axis relative to each other to cause a light pointing angle of an optical light path within the collimating lens **204** to be perpendicular to the y-axis. The collimating lens **204** and pigtail **206** may be rotated in opposite directions. For example, the collimating lens **204** may be rotated clockwise, and the pigtail **206** may be rotated counterclockwise. Step **1208** includes rotating the collimator **200** about the y-axis relative to a substrate **302** to align the light pointing angle within the collimator **200** with an optical component mounted to the substrate **302**. This process may be repeated for multiple collimators independently of one another.

**[00111]** It will be apparent to those skilled in the art that various modifications and variations can be made without departing from the spirit or scope of the invention.

**[00112]** Further, as used herein, it is intended that terms "fiber optic cables" and/or "optical fibers" include all types of single mode and multi-mode light waveguides, including one or more optical fibers that may be upcoated, colored, buffered, ribbonized and/or have other organizing or protective structure in a cable such as one or more tubes, strength members, jackets or the like. Likewise, other types of suitable optical fibers include bend-insensitive optical fibers, or any other expedient of a medium for transmitting light signals. An example of a bend-insensitive, or bend resistant, optical fiber is ClearCurve® Multimode fiber commercially available from Corning Incorporated. Suitable fibers of this type are disclosed, for example, in U.S. Patent Application Publication Nos. 2008/0166094 and 2009/0169163, which are incorporated herein by reference in their entireties.

**[00113]** Many modifications and other embodiments of the embodiments set forth herein will come to mind to one skilled in the art to which the embodiments pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the description and claims are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. It is

intended that the embodiments cover the modifications and variations of the embodiments provided they come within the scope of the appended claims and their equivalents. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed is:

1. A collimator, comprising:

a mount having a top and a bottom and defining a vertical y-axis extending therebetween, the bottom of the mount configured to be secured to a substrate;

a collimating lens secured to the mount, the collimating lens having a first front surface and a first back surface and defining a first central axis extending therebetween, the first back surface at least partially defining a first interface; and

a pigtail comprising a ferrule secured to the mount and an optical fiber having a portion positioned within the ferrule, the ferrule having a second front surface and a second back surface and defining a second central axis extending therebetween, the second central axis of the ferrule aligned with the first central axis of the collimating lens along a z-axis perpendicular to the y-axis, the optical fiber comprising an end face at least partially defining a second interface;

wherein the collimating lens and the pigtail form an optical light path from the end face of the optical fiber through the first back surface and the first front surface of the collimating lens;

wherein at least one of the first interface of the collimating lens or the second interface of the pigtail is planar and non-perpendicular to the z-axis; and

wherein the collimating lens and the pigtail are rotationally oriented around the z-axis relative to each other such that a light pointing angle of the optical light path within the collimating lens is perpendicular to the y-axis.

2. The collimator of claim 1, wherein the first interface is planar and non-perpendicular to the z-axis.

3. The collimator of either of claims 1 or 2, wherein the second interface is planar and non-perpendicular to the z-axis.

4. The collimator of any of claims 1-3, wherein the first interface and the second interface are planar and non-perpendicular to the z-axis.

5. The collimator of any of claims 1-4, wherein the mount comprises a glass tube having an outer surface defining a square cross-sectional shape.

6. The collimator of any of claims 1-5, wherein the mount comprises a v-groove mount.

7. The collimator of any of claims 1-6, wherein the end face of the optical fiber is coplanar with the second front surface of the ferrule.

8. A micro-optical assembly, comprising:
a substrate comprising a top surface;
a first optical component mounted to a top surface of the substrate; and
a first collimator according to claim 1 mounted to the top surface of the substrate;
wherein the light pointing angle of the optical light path within the collimating lens of the first collimator is non-parallel to the z-axis; and
wherein the first collimator is rotationally oriented around the y-axis relative to the substrate so that the light pointing angle within the first collimator is aligned with the first optical component.

9. The micro-optical assembly of claim 8,
further comprising an array comprising the first collimator and a second collimator according to claim 1 mounted to the substrate;
wherein the collimating lens and the pigtail of the second collimator are rotationally oriented around the z-axis relative to each other independent of the first collimator.

10. The micro-optical assembly of either of claims 8 or 9,

further comprising a second optical component mounted to the top surface of the substrate;

wherein the second collimator is rotationally oriented around the y-axis relative to the substrate so that the light pointing angle within the second collimator is aligned with the second optical component, the second collimator rotationally oriented around the y-axis independent of the first collimator.

11. A method for tuning a collimator, comprising:

positioning a collimating lens to a mount of a collimator, the collimating lens having a first front surface and a second back surface and defining a first central axis extending therebetween, the mount having a top and a bottom and defining a vertical y-axis extending therebetween;

aligning a second central axis of a ferrule of a pigtail with the first central axis of the collimating lens along a z-axis perpendicular to the vertical y-axis, the ferrule having a second front surface and a second back surface and the second central axis extending therebetween; and

rotating at least one of the pigtail or the collimating lens about the z-axis relative to each other to cause a light pointing angle of an optical light path within the collimating lens to be perpendicular to the y-axis, the optical light path extending from an end face of an optical fiber of the pigtail through the first back surface and the first front surface of the collimating lens, the optical fiber having a portion positioned within the ferrule.

12. The method of claim 11, wherein the step of rotating at least one of the pigtail or the collimating lens about the z-axis relative to each other comprises rotating the pigtail about the z-axis relative to the collimating lens.

13. The method of either of claims 11 or 12, wherein the step of rotating at least one of the pigtail or the collimating lens about the z-axis relative to each other comprises rotating the collimating lens about the z-axis relative to the pigtail.

14. The method of any of claims 11-13, wherein the step of rotating at least one of the pigtail or the collimating lens about the z-axis relative to each other comprises:

rotating the pigtail in a first direction about the z-axis relative to the collimating lens; and

rotating the collimating lens in a second direction about the z-axis relative to the collimating lens, the second direction opposite the first direction.

15. The method of any of claims 11-14, wherein the step of positioning a collimating lens to a mount of a collimator comprises positioning a collimating lens within a bore of a glass tube having an outer surface with a square cross-sectional shape.

16. The method of any of claims 11-15, wherein the step of positioning a collimating lens to a mount of a collimator comprises positioning a collimating lens on a v-groove mount.

17. The method of any of claims 11-16, further comprising rotating the collimator about the y-axis relative to a substrate to align the light pointing angle within the first collimator with a first optical component mounted to the substrate.

18. A method of assembling a micro-optical assembly, comprising positioning an array of collimators on the substrate, the array comprising a first collimator tuned according to the method of claim 11, and a second collimator tuned according to the method of any of claims 11-17.

19. The method of claim 18, further comprising tuning the second collimator along the y-axis independently of the first collimator.

20. The method of claim 19, further comprising tuning the second collimator around the y-axis independently of the first collimator.

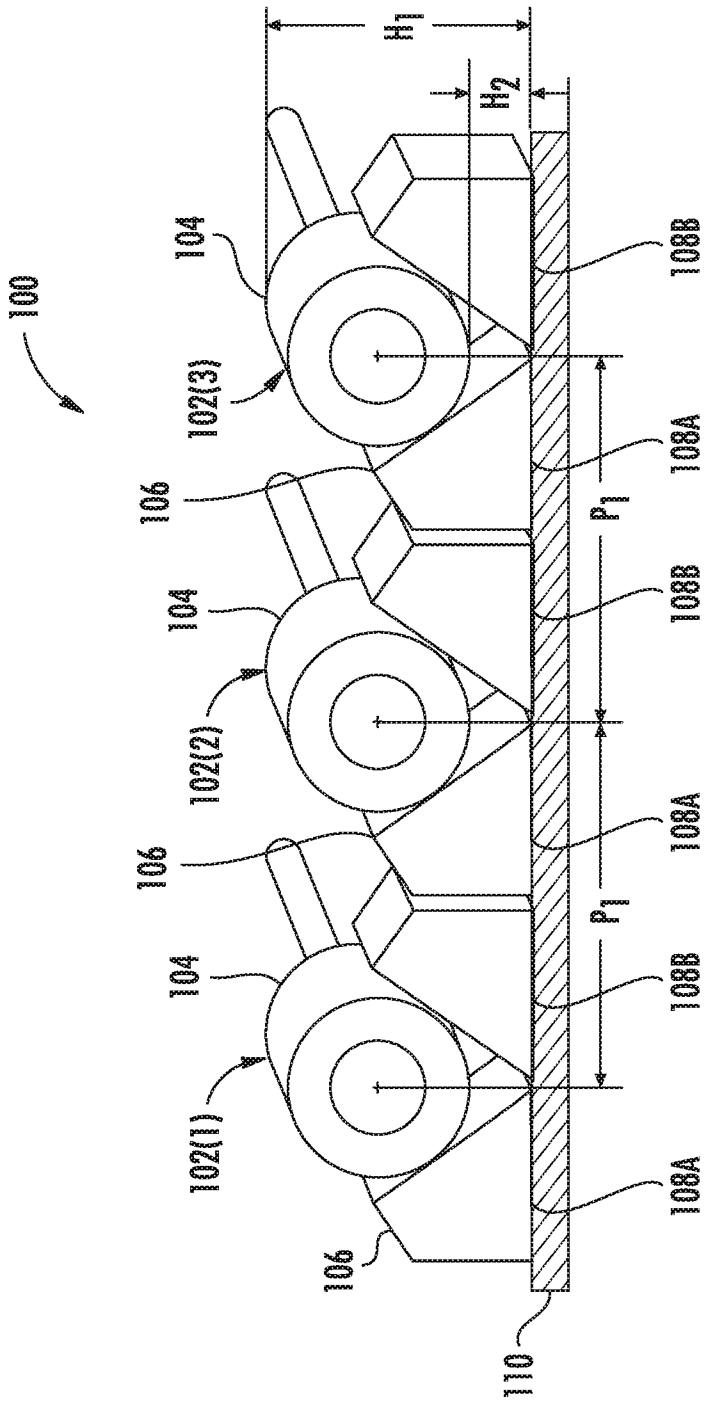
100
H1
H2
104
102(3)
106
104
102(2)
106
104
102(1)
106
108B
108A
P1
108B
108A
P1
108B
108A
110

FIG. 1

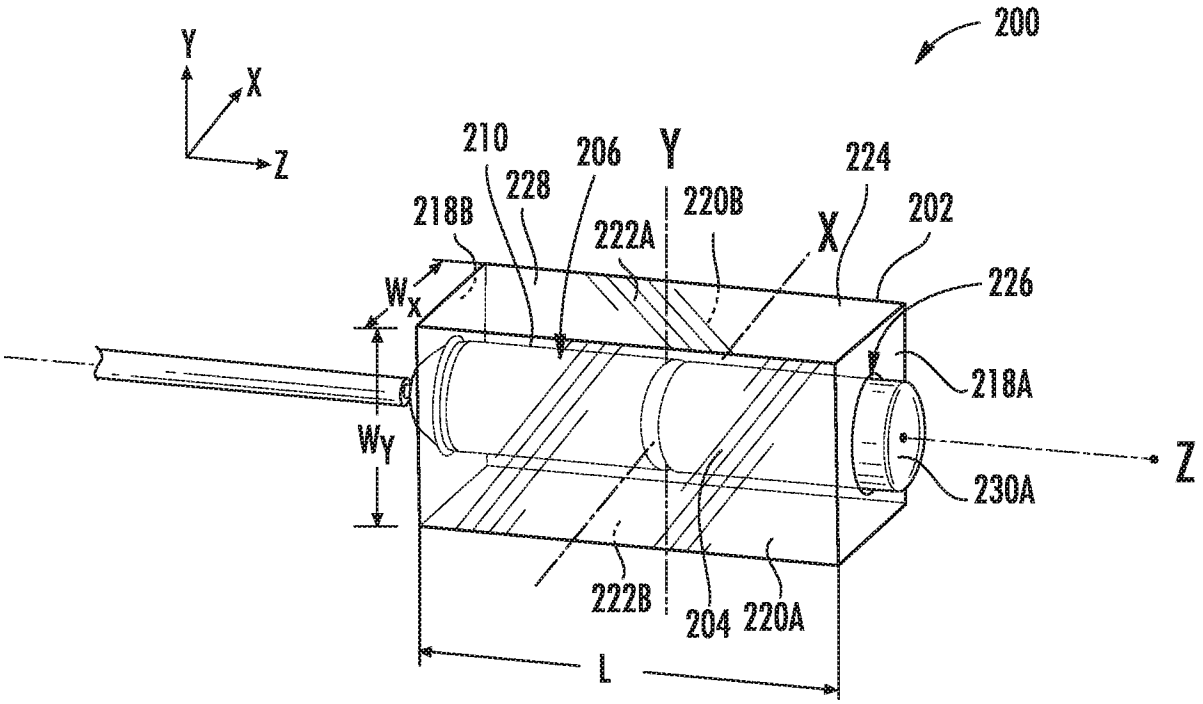
200
Y
X
Z
210
206
Y
224
228
218B
220B
202
222A
X
226
Wx
218A
Wy
Z
230A
222B
204
220A
L

FIG. 2A

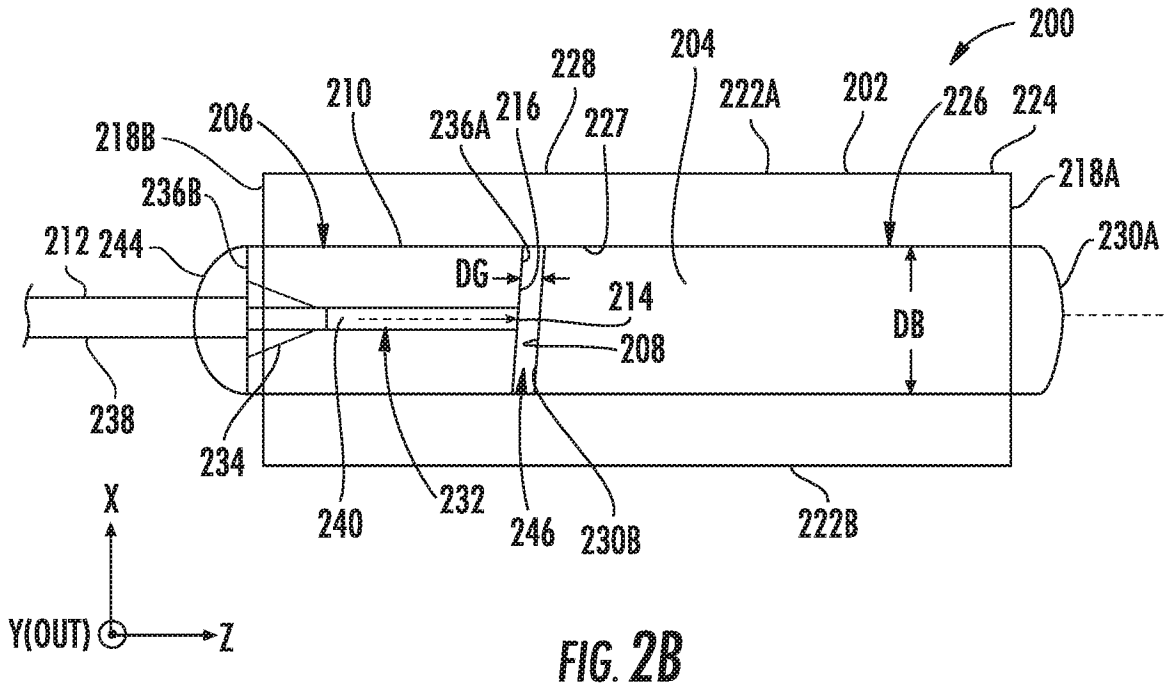
200
204
228
210
222A
202
226
224
206
236A
216
227
218B
218A
236B
230A
212
244
DG
214
DB
208
238
234
240
232
246
230B
222B
X
Y(OUT)
Z

FIG. 2B

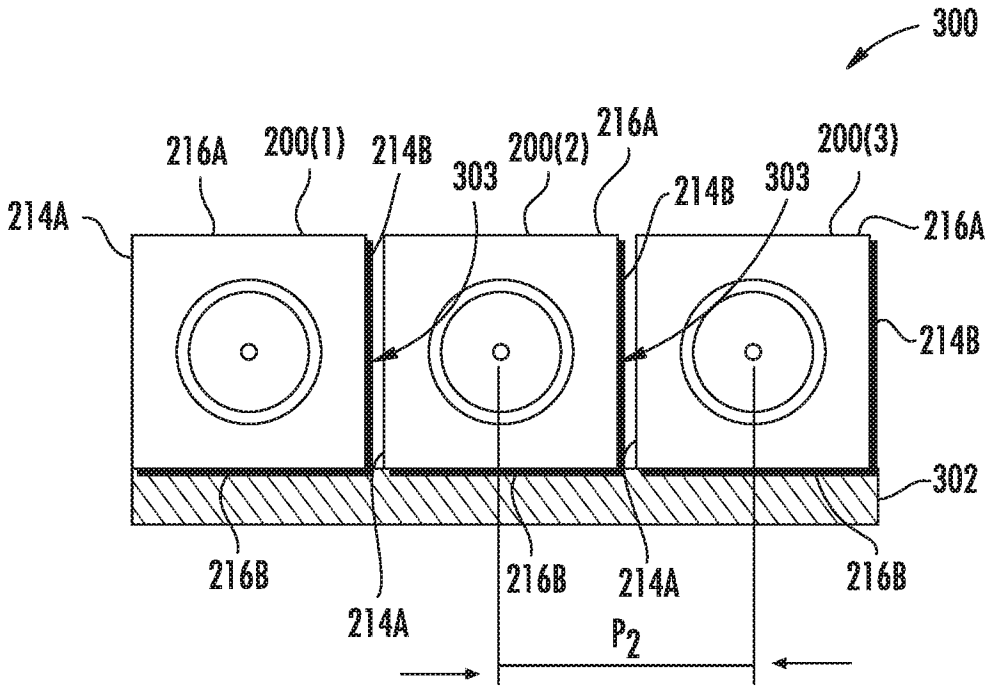
300
216A
200(1)
214B
303
200(2)
216A
214B
303
200(3)
214A
216A
214B
302
216B
214A
216B
214A
216B
$P_2$

FIG. 3A

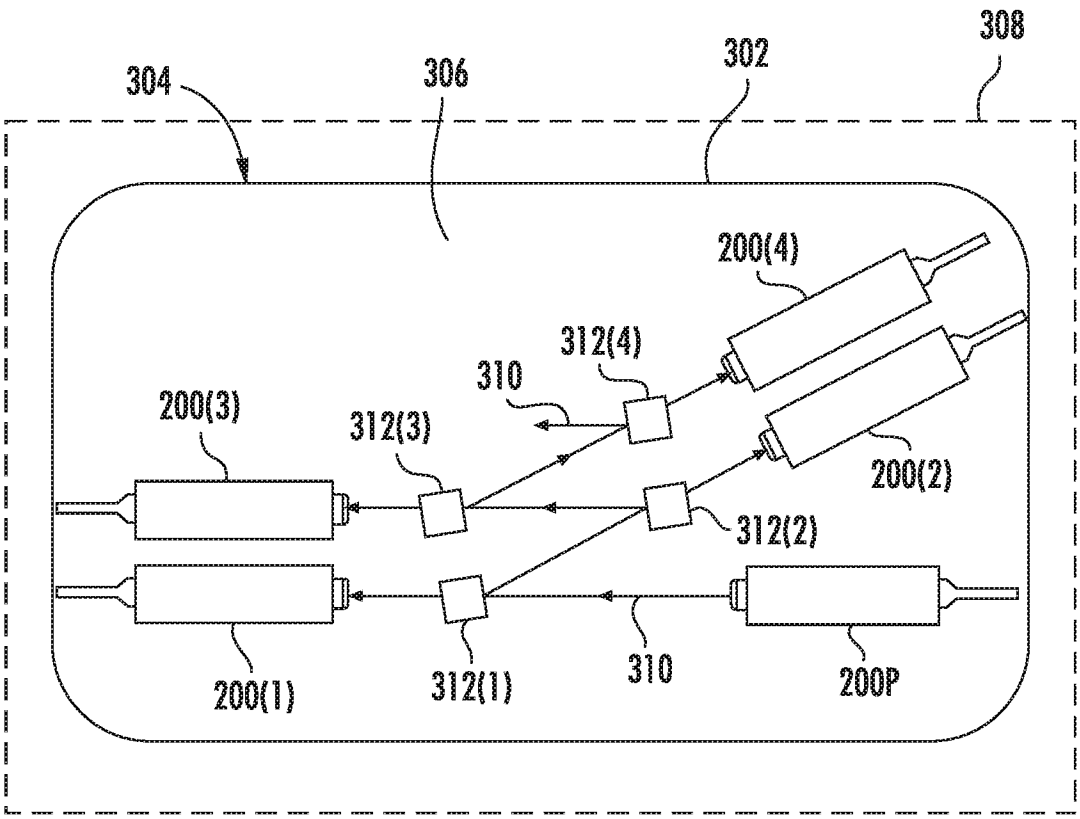
308
304
306
302
200(4)
312(4)
310
200(3)
312(3)
200(2)
312(2)
200(1)
312(1)
310
200P

FIG. 3B

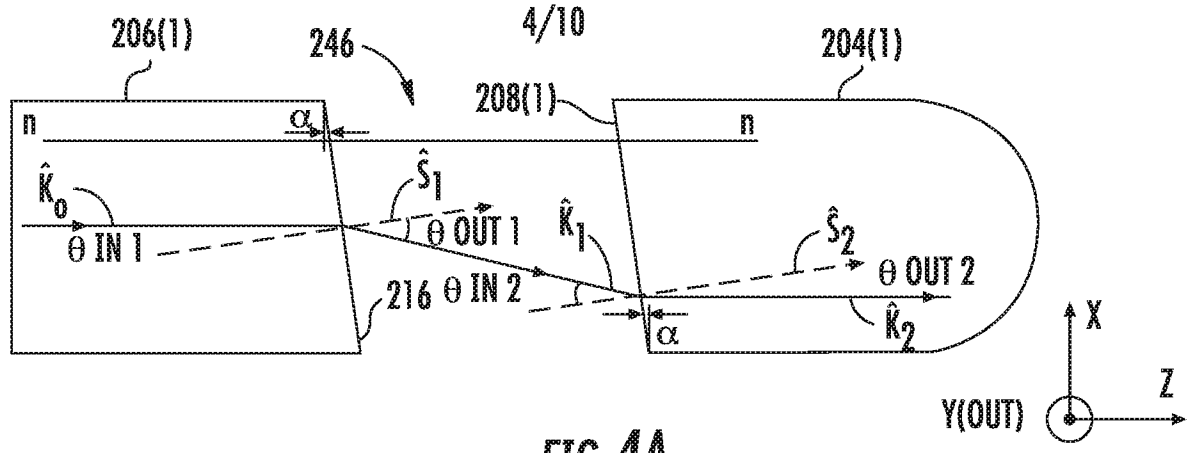


FIG. 4A

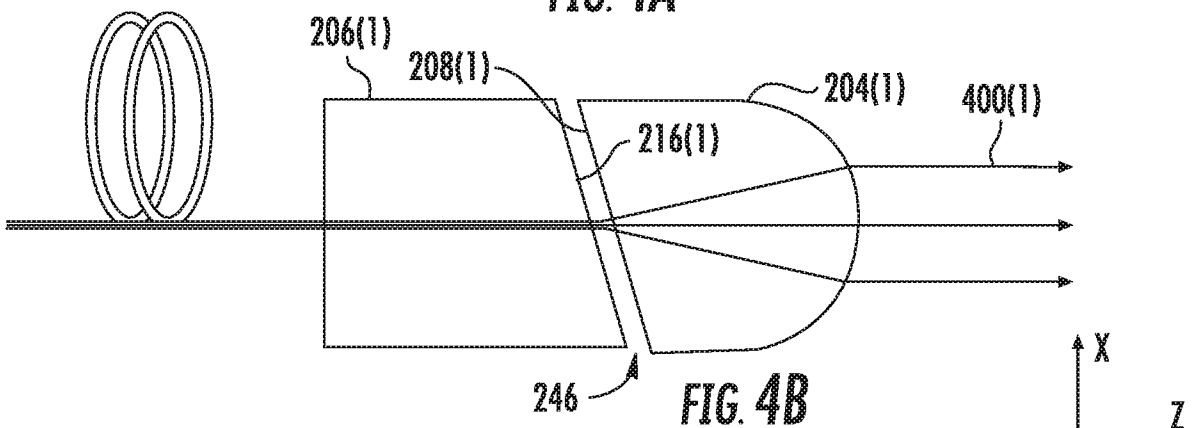


FIG. 4B

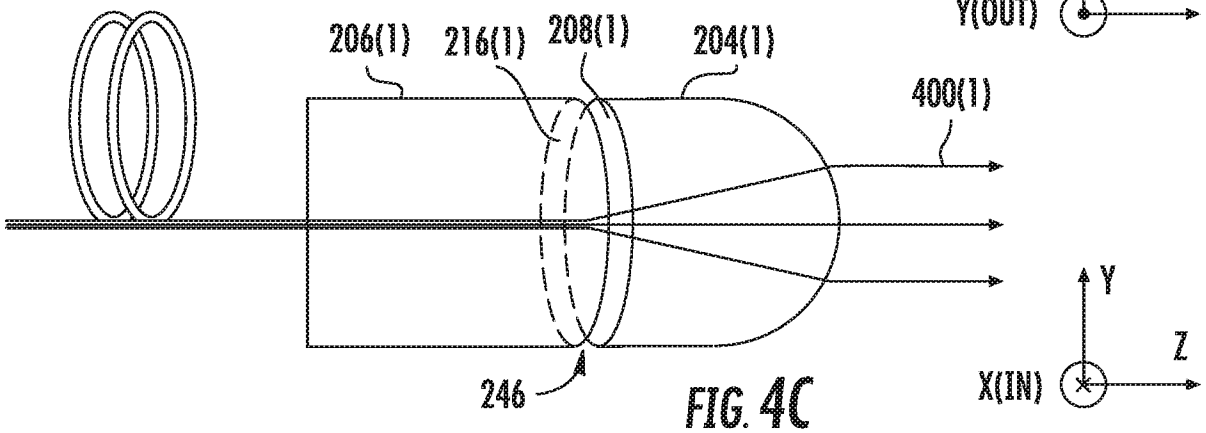


FIG. 4C

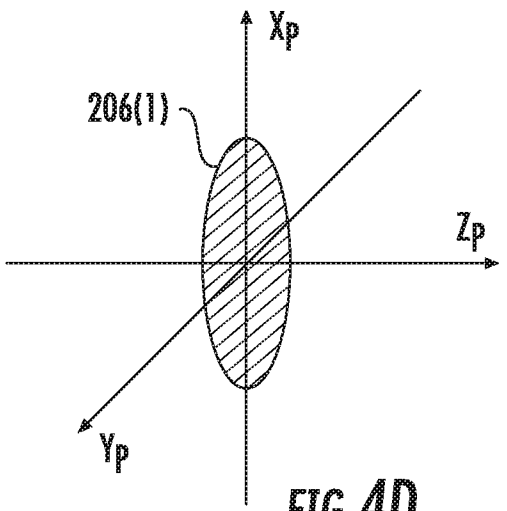


FIG. 4D

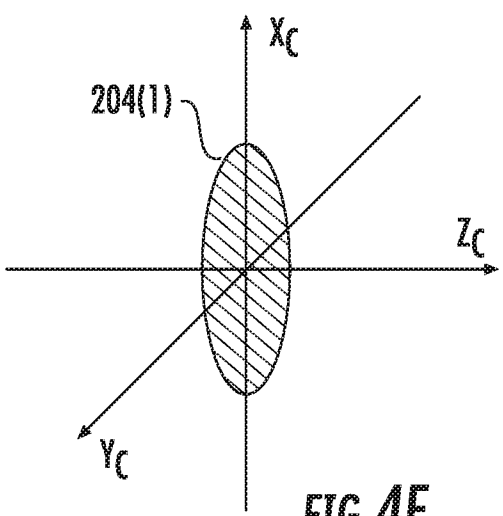


FIG. 4E

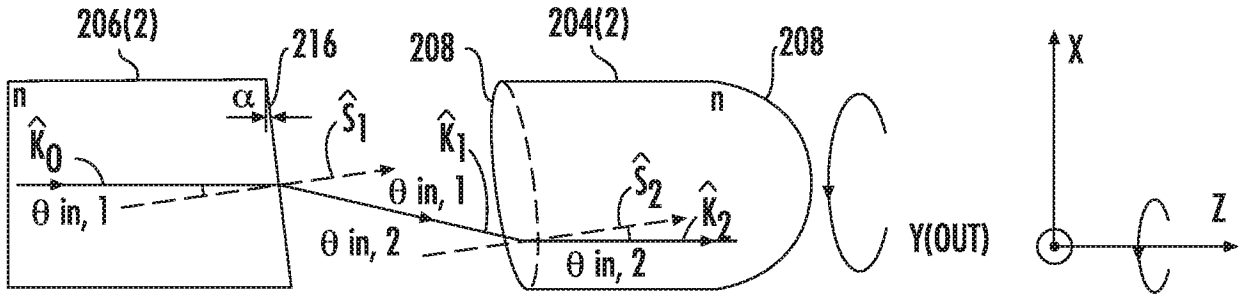


FIG. 5A

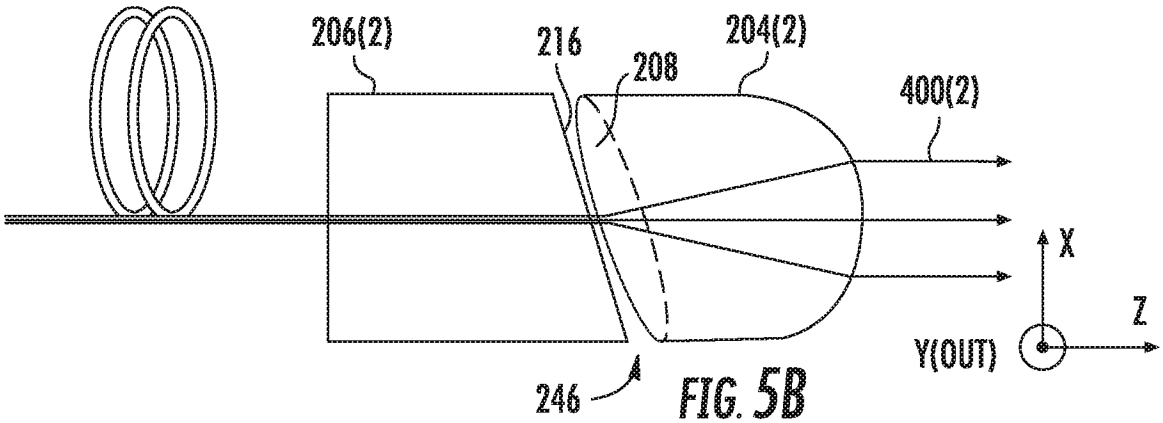


FIG. 5B

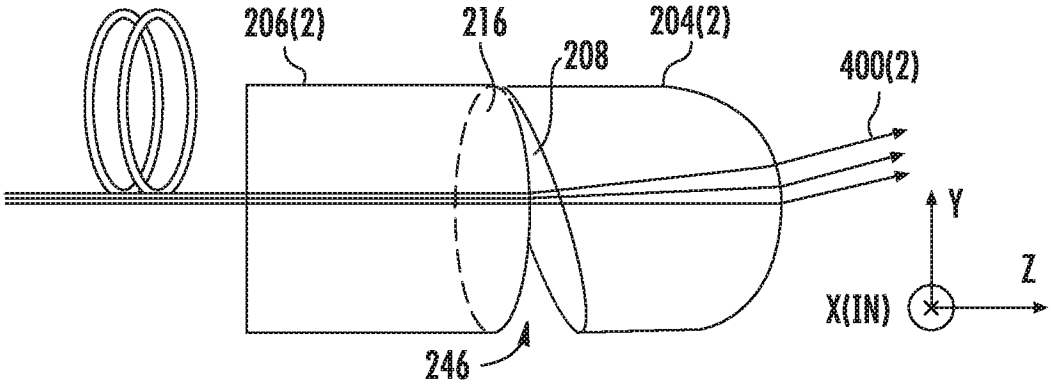


FIG. 5C

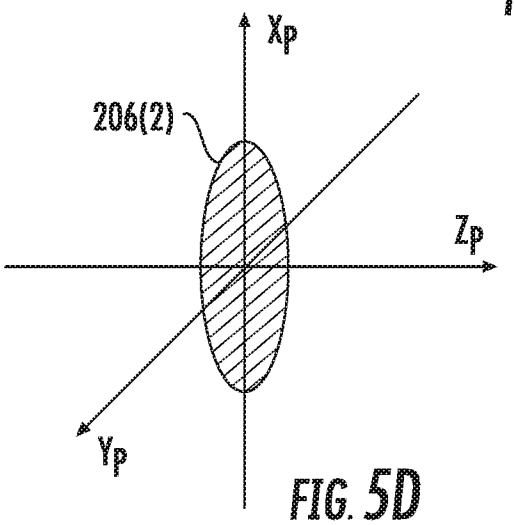


FIG. 5D

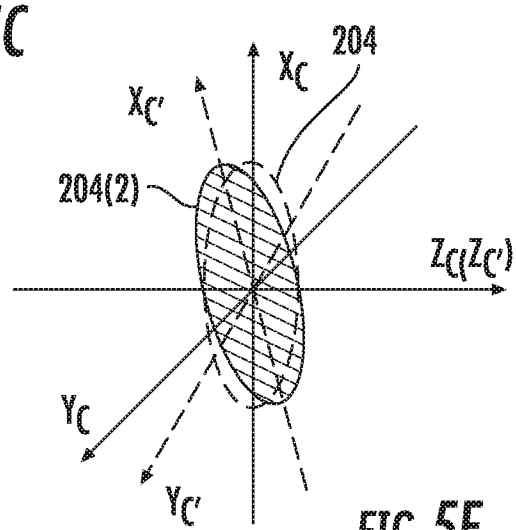


FIG. 5E

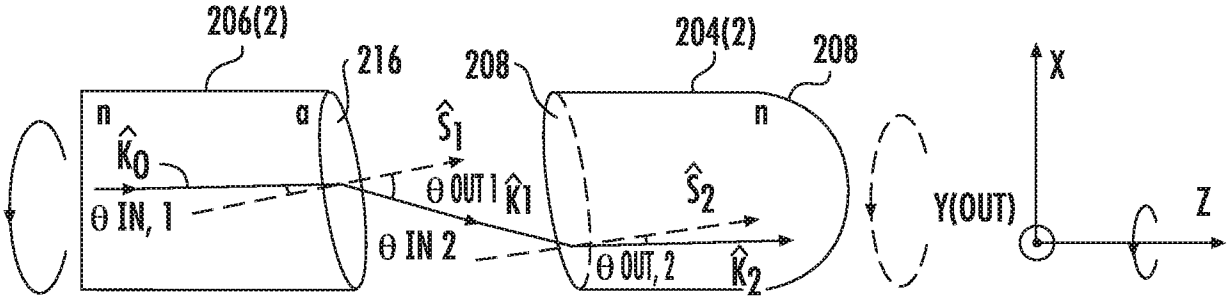


FIG. 6A

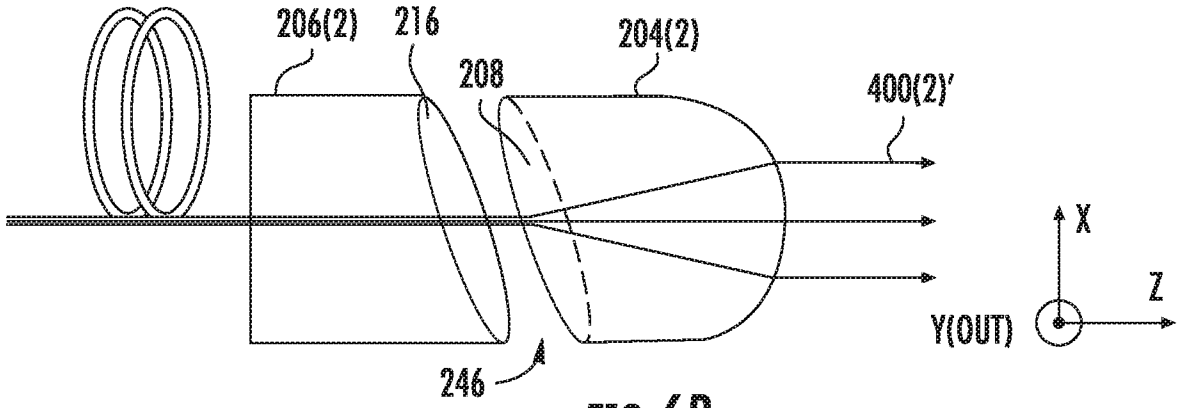


FIG. 6B

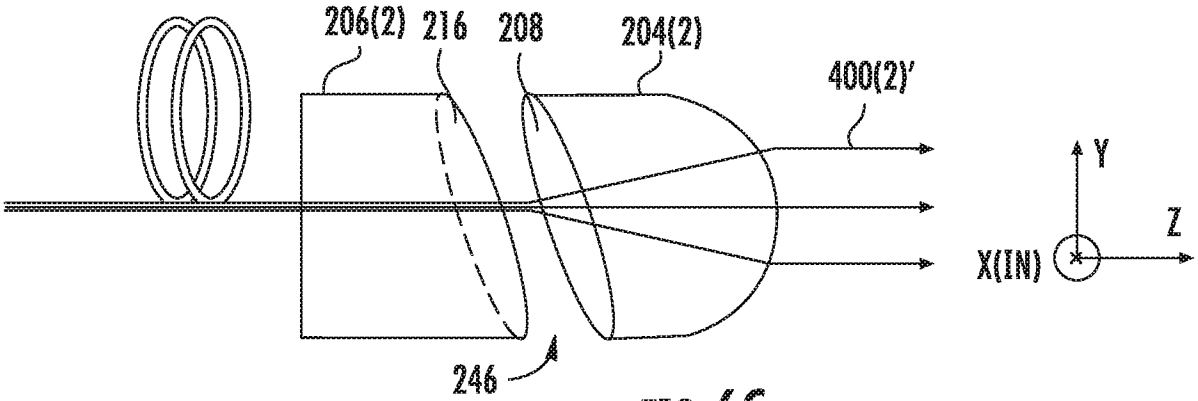


FIG. 6C

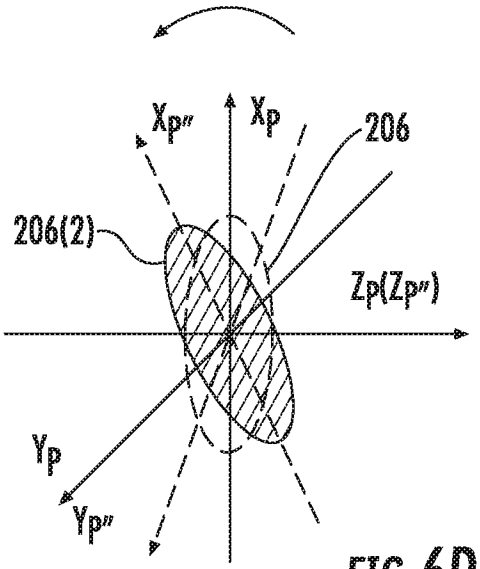


FIG. 6D

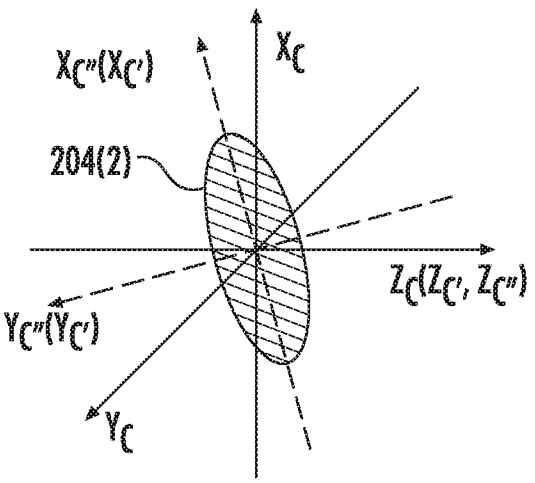


FIG. 6E

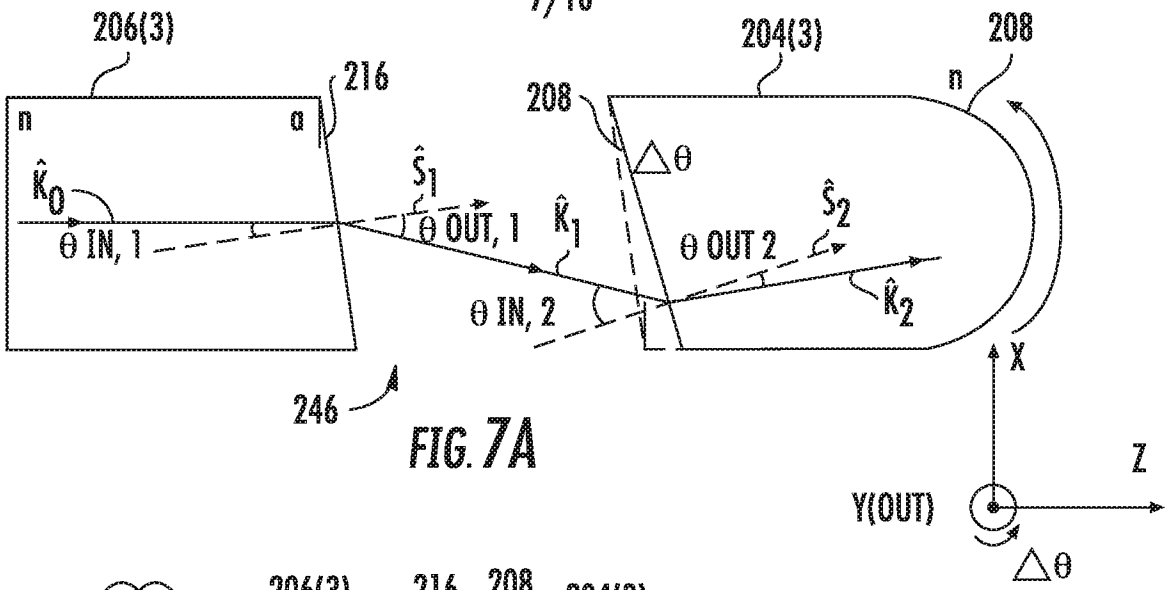


FIG. 7A

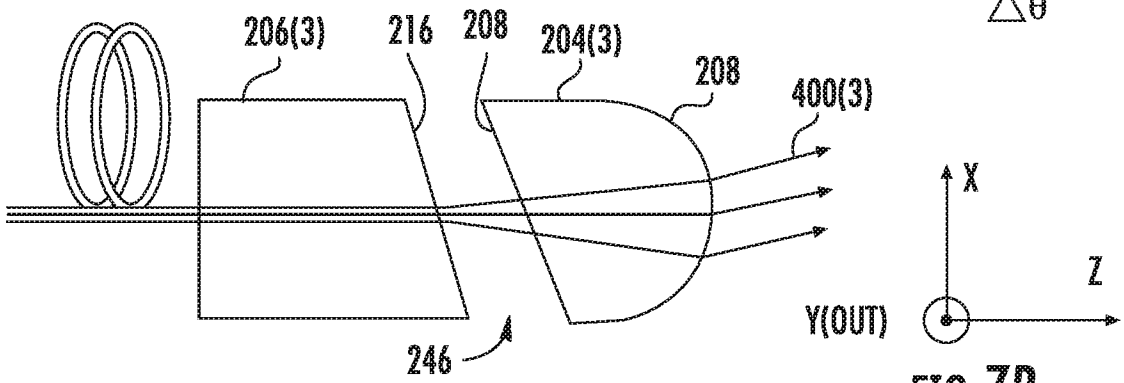


FIG. 7B

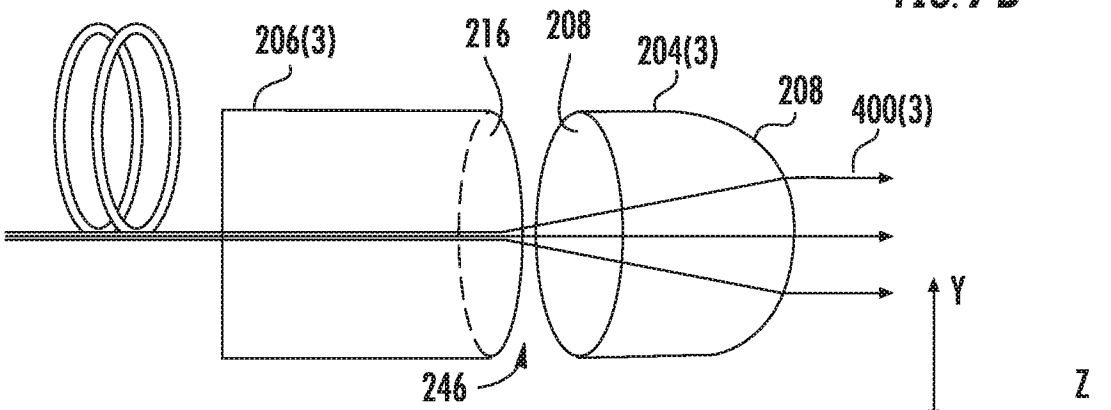


FIG. 7C

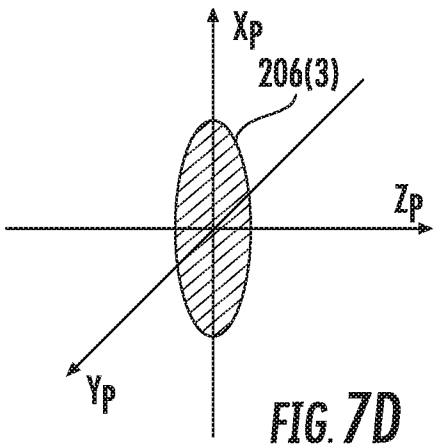


FIG. 7D

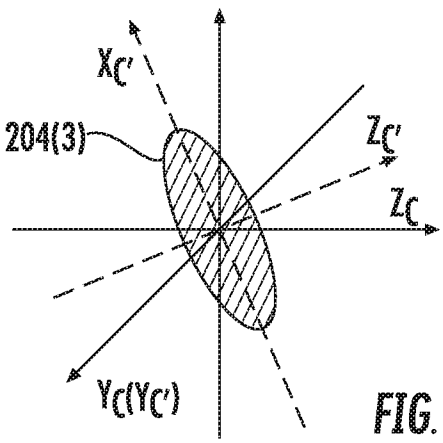


FIG. 7E

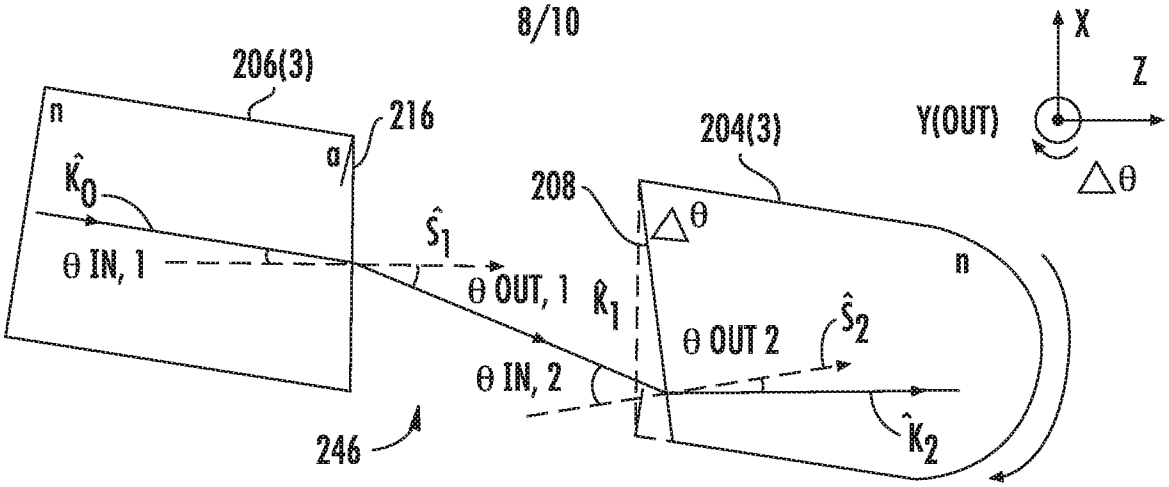


FIG. 8A

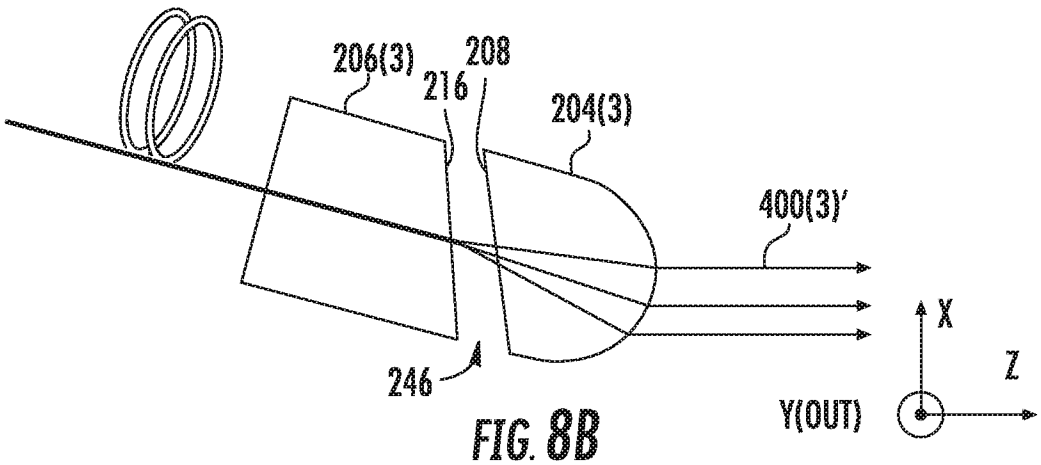


FIG. 8B

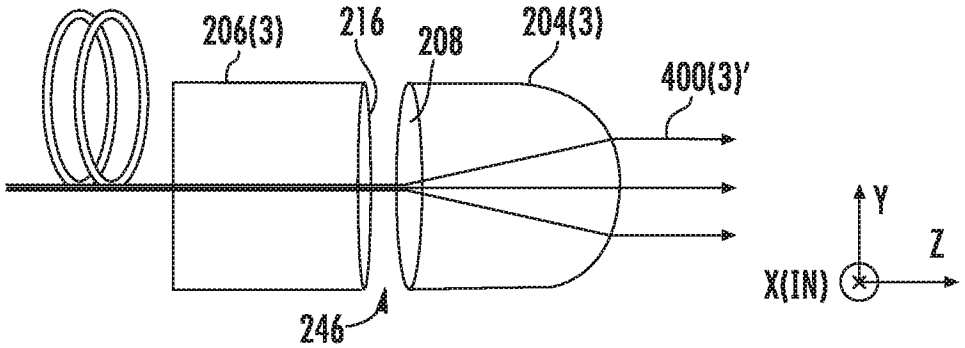


FIG. 8C

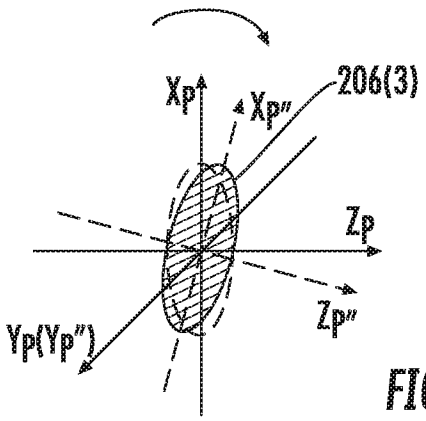


FIG. 8D

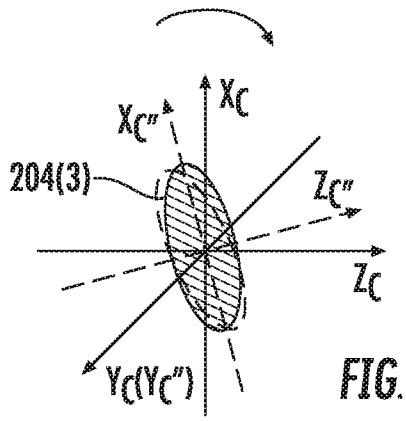


FIG. 8E

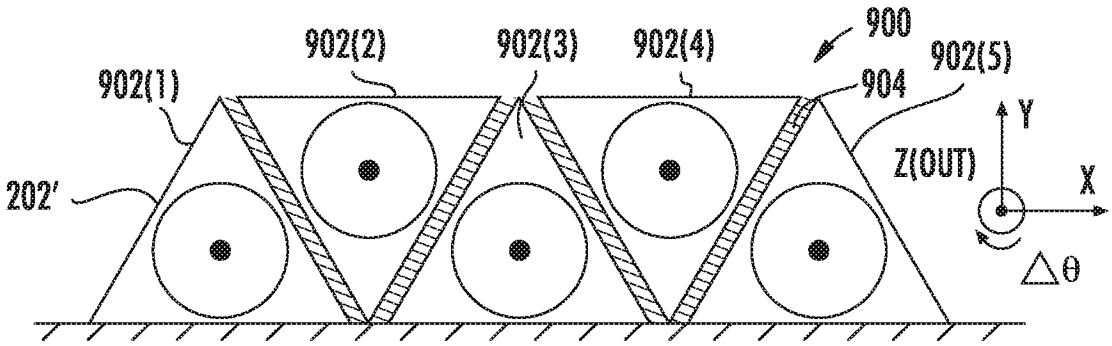


FIG. 9

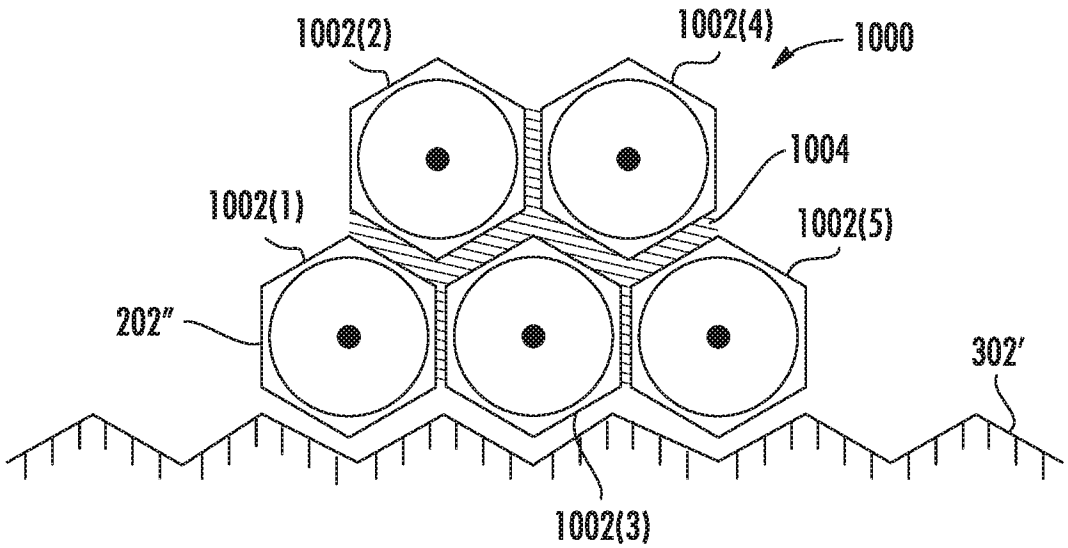


FIG. 10

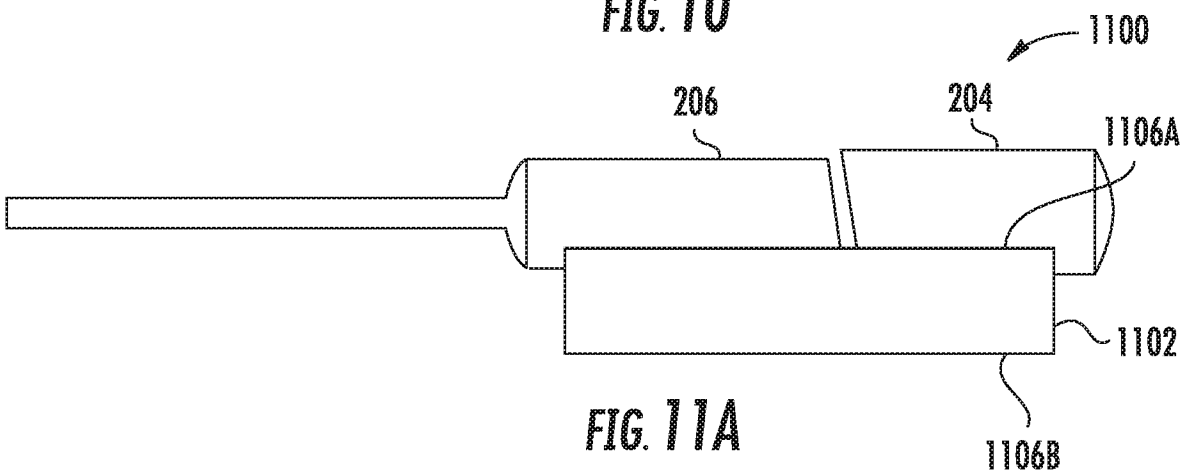


FIG. 11A

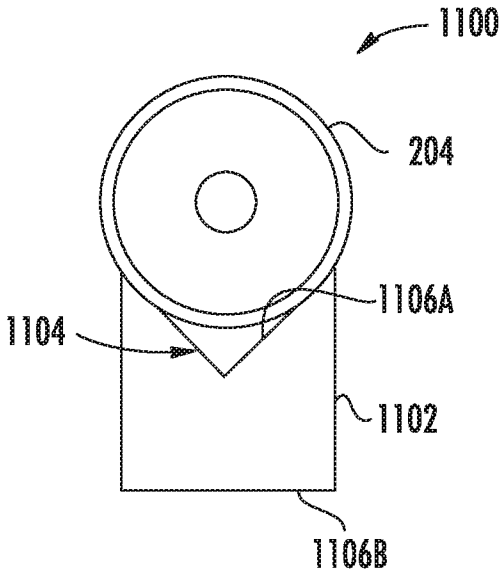


FIG. 11B

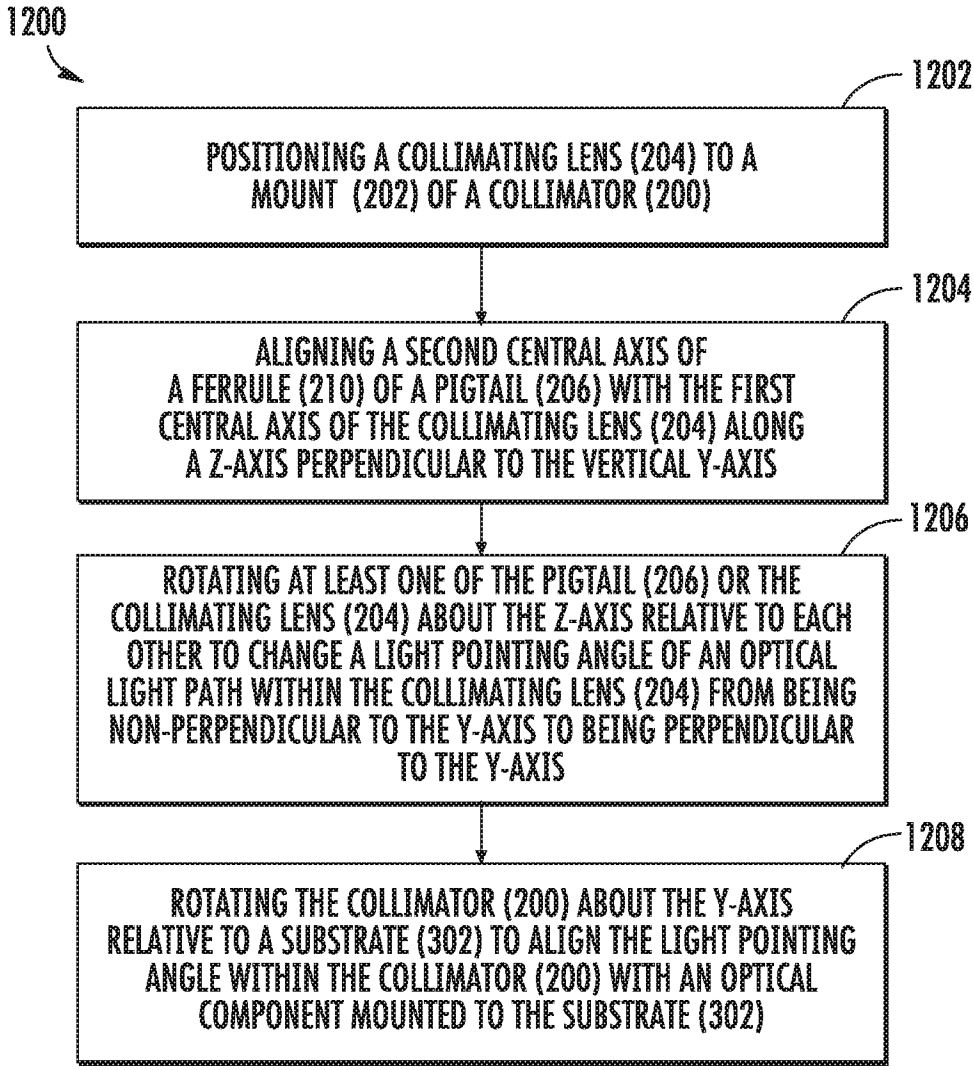


FIG. 12

# INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/056058

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B6/32
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br>Y | US 2002/181865 A1 (JANG WIN-YANN [TW] ET AL) 5 December 2002 (2002-12-05)<br>paragraphs [0017] - [0019]; figures 1,2,5 | 1-4,7,11-14<br>8-10,17-20 |
| X | US 5 809 193 A (TAKAHASHI MITSUO [JP])<br>15 September 1998 (1998-09-15)<br>column 5, line 52 - column 6, line 49;<br>figures 1a-2d | 1-7,11-16 |
| X | US 2003/150102 A1 (HWANG MYEON-SOON [KR] ET AL) 14 August 2003 (2003-08-14)<br>paragraphs [0048] - [0050]; figures 5a-6b | 1-4,7,11-14 |
| X | US 6 168 319 B1 (FRANCIS KURT R [US])<br>2 January 2001 (2001-01-02)<br>column 5, lines 20-44; figure 1 | 1-4,7,11-14 |

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 10 January 2019 | 17/01/2019 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Ciarrocca, Marco |

1

Form PCT/ISA/210 (second sheet) (April 2005)

# INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/056058

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | US 7 224 865 B1 (WANG DAOYI [US] ET AL) 29 May 2007 (2007-05-29) column 1, lines 15-50; figure 1 | 8-10, 17-20 |
| A | US 6 666 588 B1 (THORSTEN NEAL H [US] ET AL) 23 December 2003 (2003-12-23) figures 2,3 | 1,6,11, 16 |

1

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2018/056058

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---|---|---|
| US 2002181865 A1 | 05-12-2002 | NONE | |
| US 5809193 A | 15-09-1998 | CA 2195596 A1 | 24-01-1998 |
| | | GB 2315564 A | 04-02-1998 |
| | | JP 2983177 B2 | 29-11-1999 |
| | | JP H1039166 A | 13-02-1998 |
| | | US 5809193 A | 15-09-1998 |
| US 2003150102 A1 | 14-08-2003 | CN 1438774 A | 27-08-2003 |
| | | JP 2003241010 A | 27-08-2003 |
| | | KR 20030068281 A | 21-08-2003 |
| | | TW I221939 B | 11-10-2004 |
| | | US 2003150102 A1 | 14-08-2003 |
| US 6168319 B1 | 02-01-2001 | AU 1568401 A | 05-03-2001 |
| | | TW 500935 B | 01-09-2002 |
| | | US 6168319 B1 | 02-01-2001 |
| | | WO 0111403 A1 | 15-02-2001 |
| US 7224865 B1 | 29-05-2007 | NONE | |
| US 6666588 B1 | 23-12-2003 | NONE | |