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(54) **OPTICAL INTERCONNECTS IN MICROELECTRONICS BASED ON AZIMUTHALLY ASYMMETRIC LONG-PERIOD FIBER GRATING COUPLERS**

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G02B 6/12 (2006.01)
G02B 6/34 (2006.01)

(52) **U.S. Cl.** **385/14**; 385/37; 385/48

(58) **Field of Classification Search** 385/37, 385/14

See application file for complete search history.

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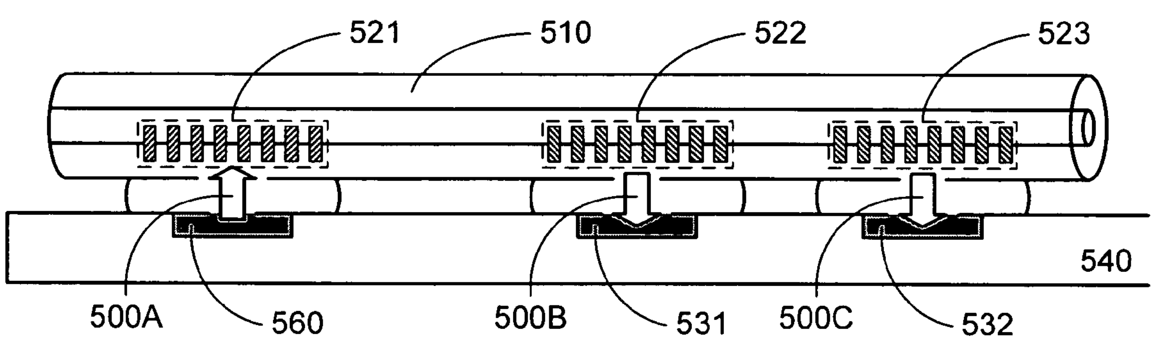
(57) **ABSTRACT**

Systems and methods, including azimuthally asymmetric fiber gratings are disclosed.

33 Claims, 11 Drawing Sheets



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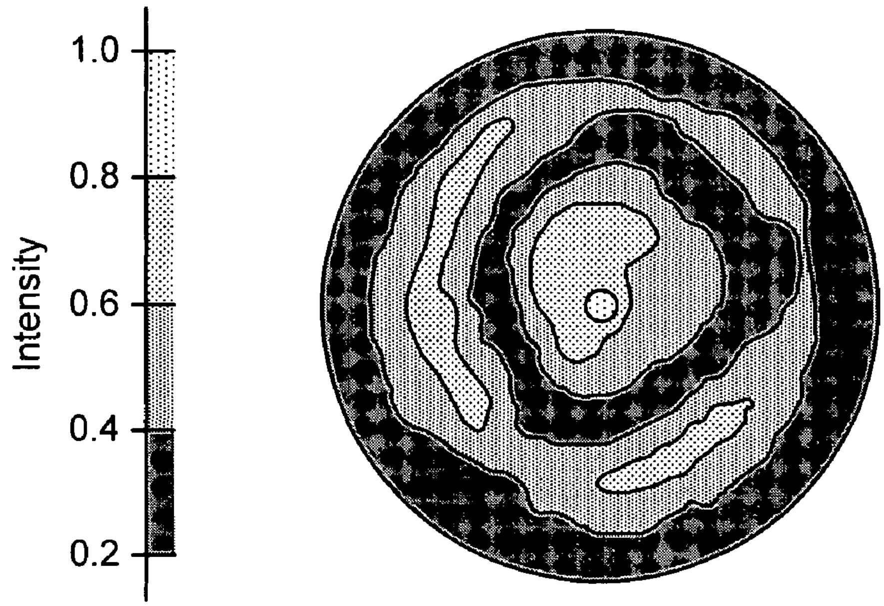
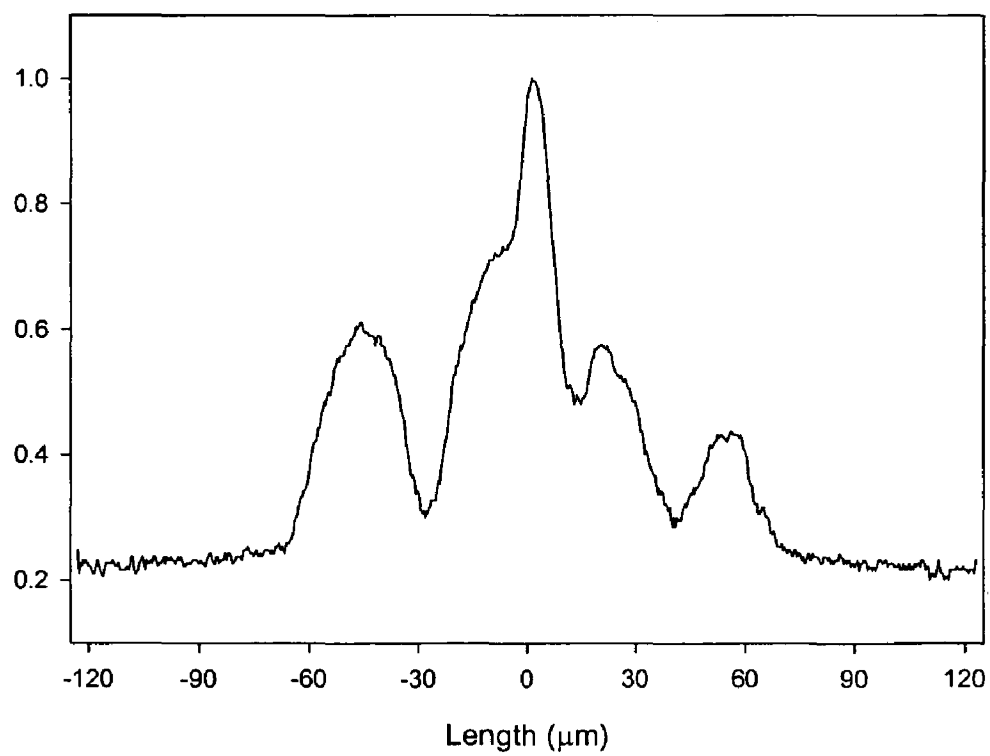

1.0
0.8
0.6
0.4
0.2
Intensity

FIG. 1A


1.0
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0.2
-120
-90
-60
-30
0
30
60
90
120
Length (μm)

FIG. 1B

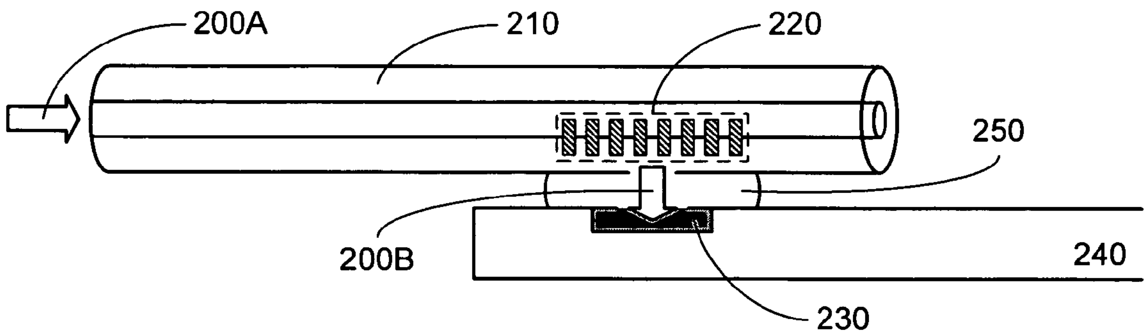


FIG. 2A

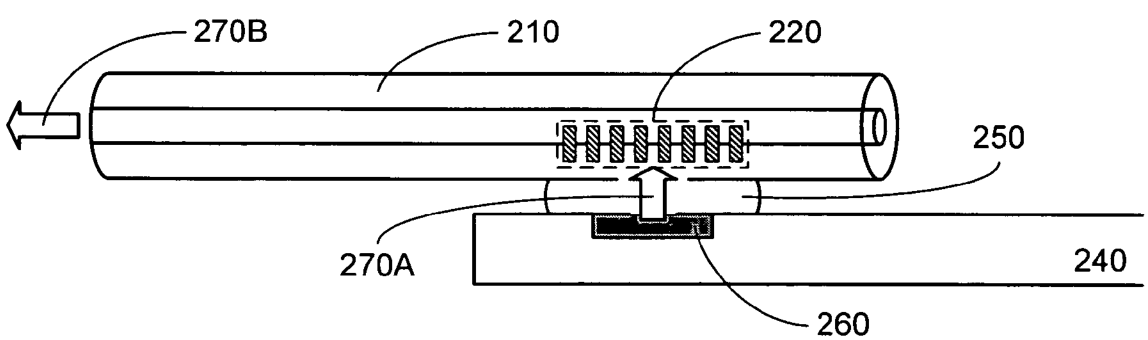
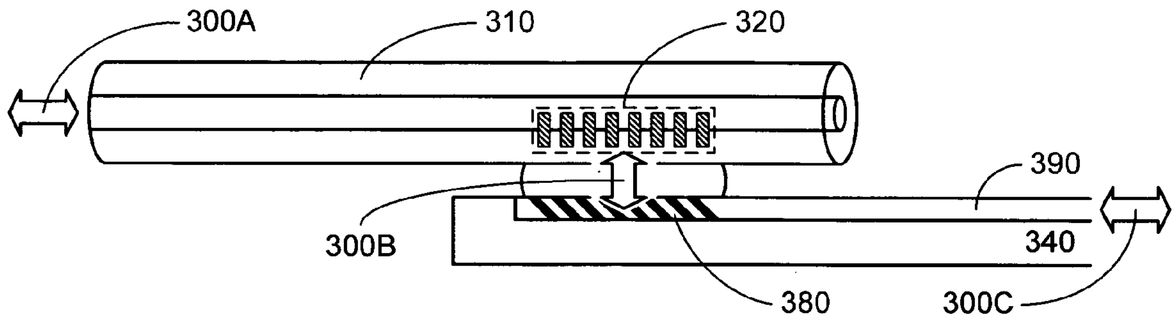


FIG. 2B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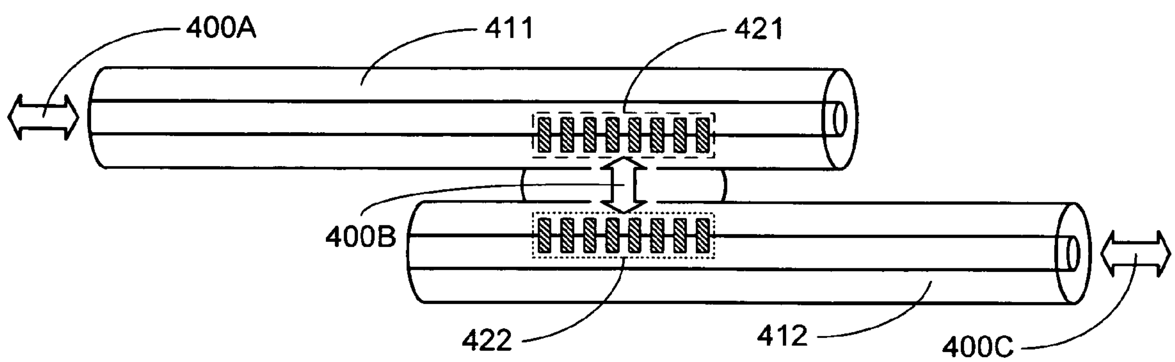
320
390
300B
340
380
300C

FIG. 3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421
400B
422
412
400C

FIG. 4

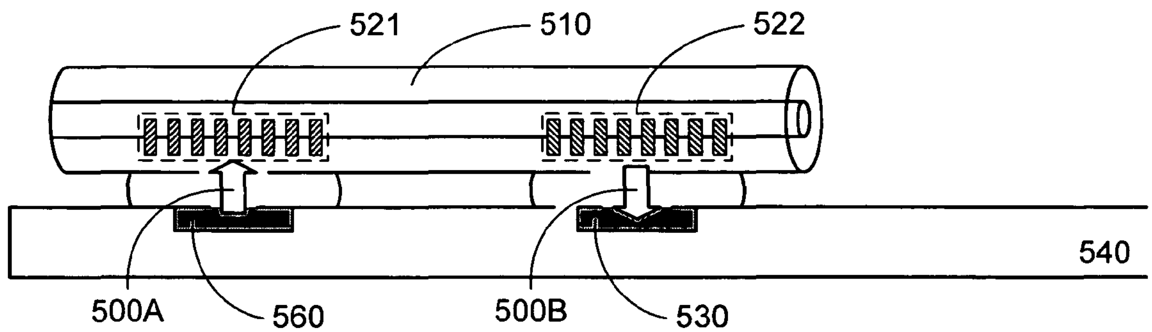

521
510
522
540
500A
560
500B
530

FIG. 5A

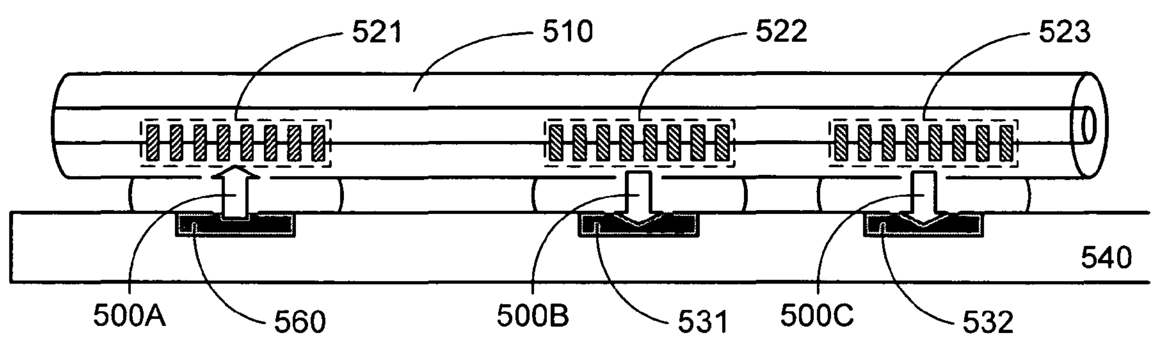

521
510
522
523
540
500A
560
500B
531
500C
532

FIG. 5B

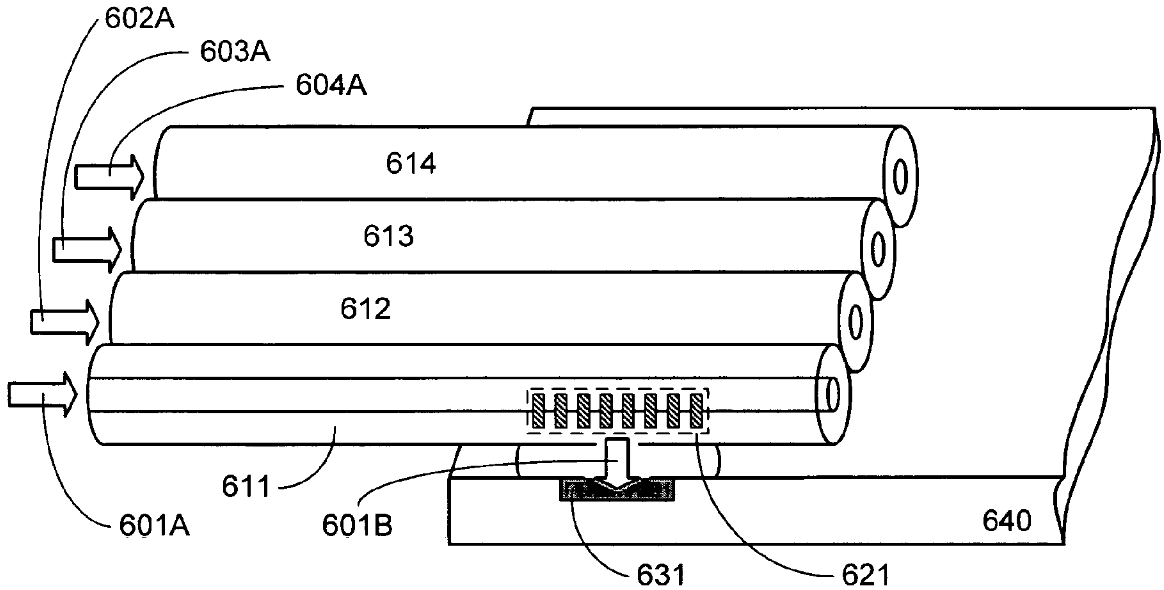

602A
603A
604A
614
613
612
611
601A
601B
631
621
640

FIG. 6A

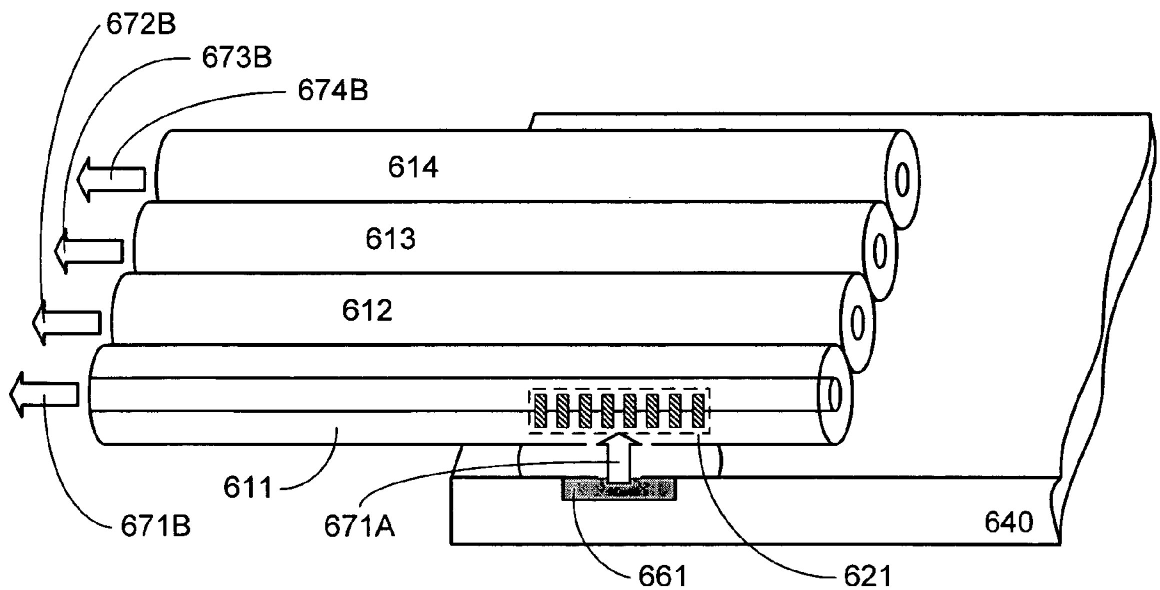

672B
673B
674B
614
613
612
611
671B
671A
661
621
640

FIG. 6B

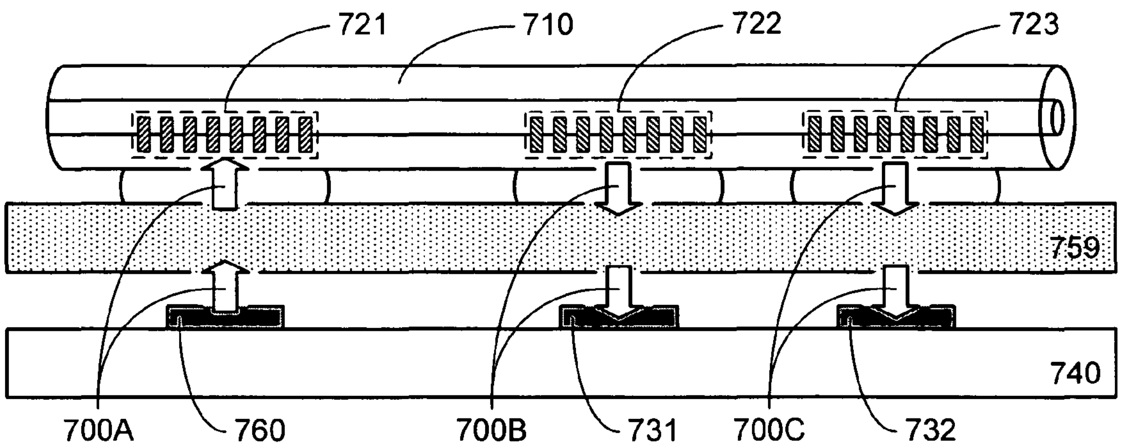


FIG. 7

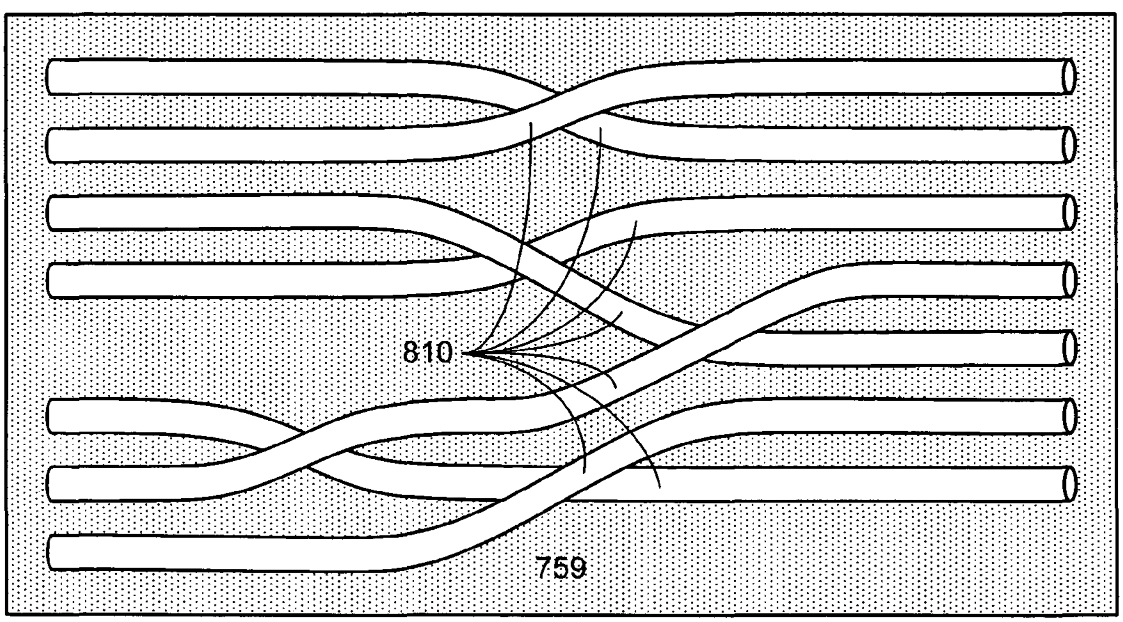


FIG. 8A

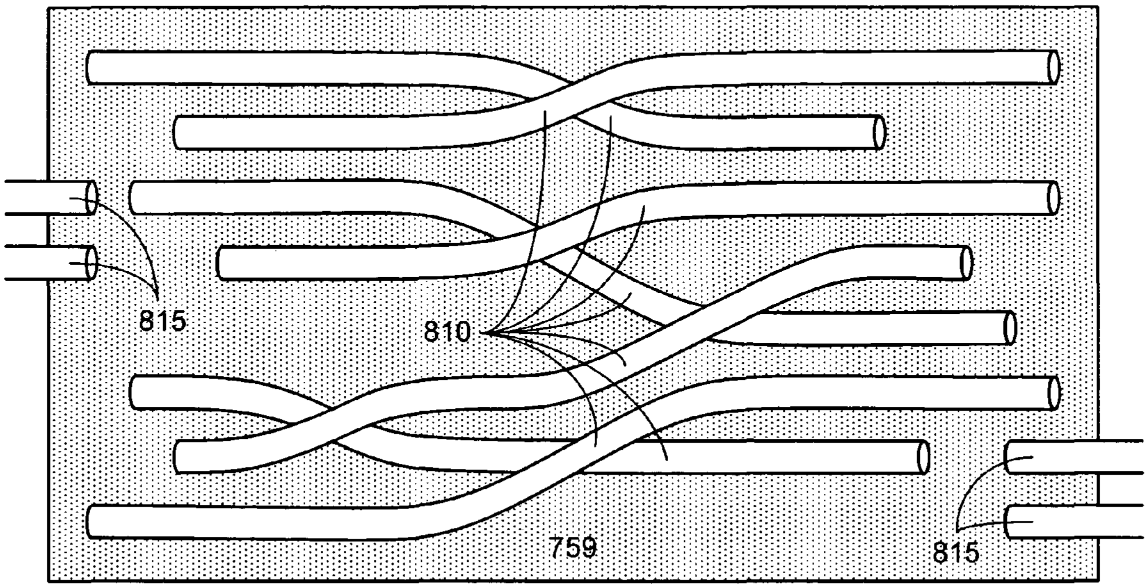


FIG. 8B

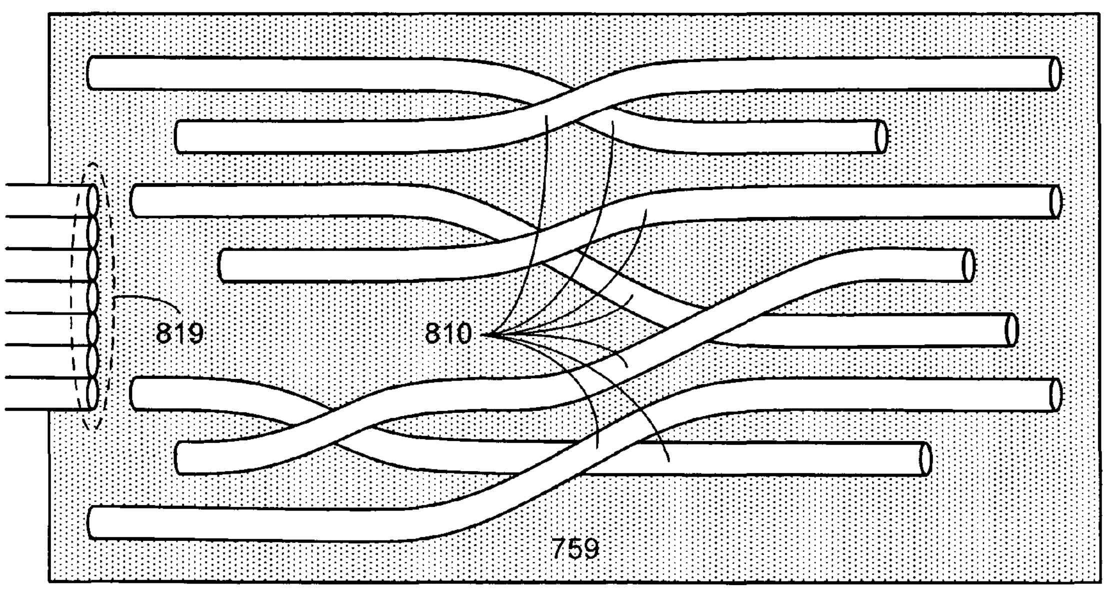


FIG. 8C

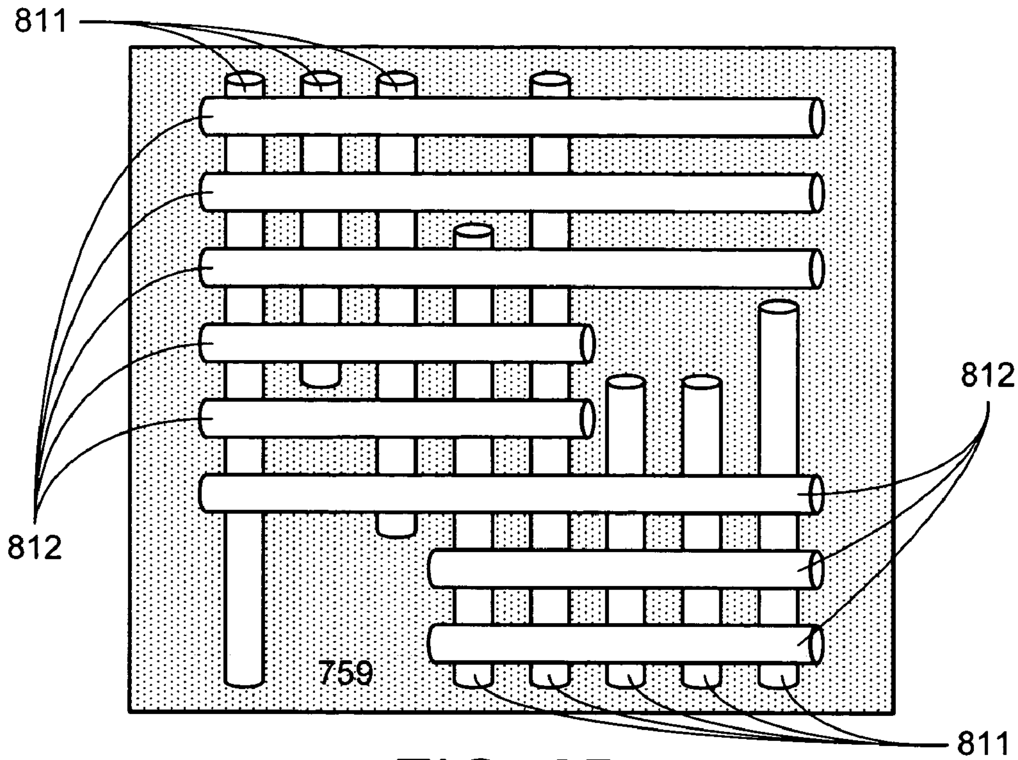


FIG. 8D

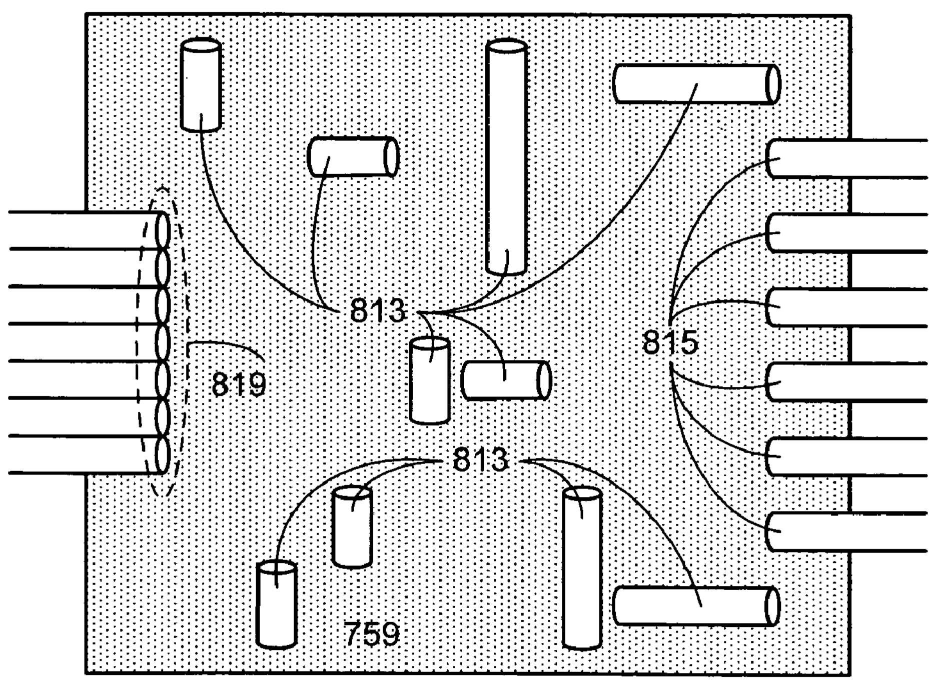


FIG. 8E

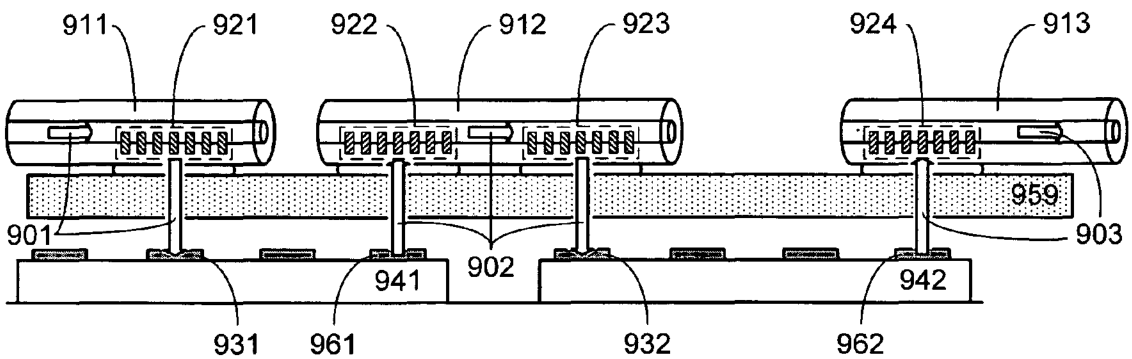

911
921
922
912
923
924
913
959
901
903
902
941
942
931
961
932
962

FIG. 9

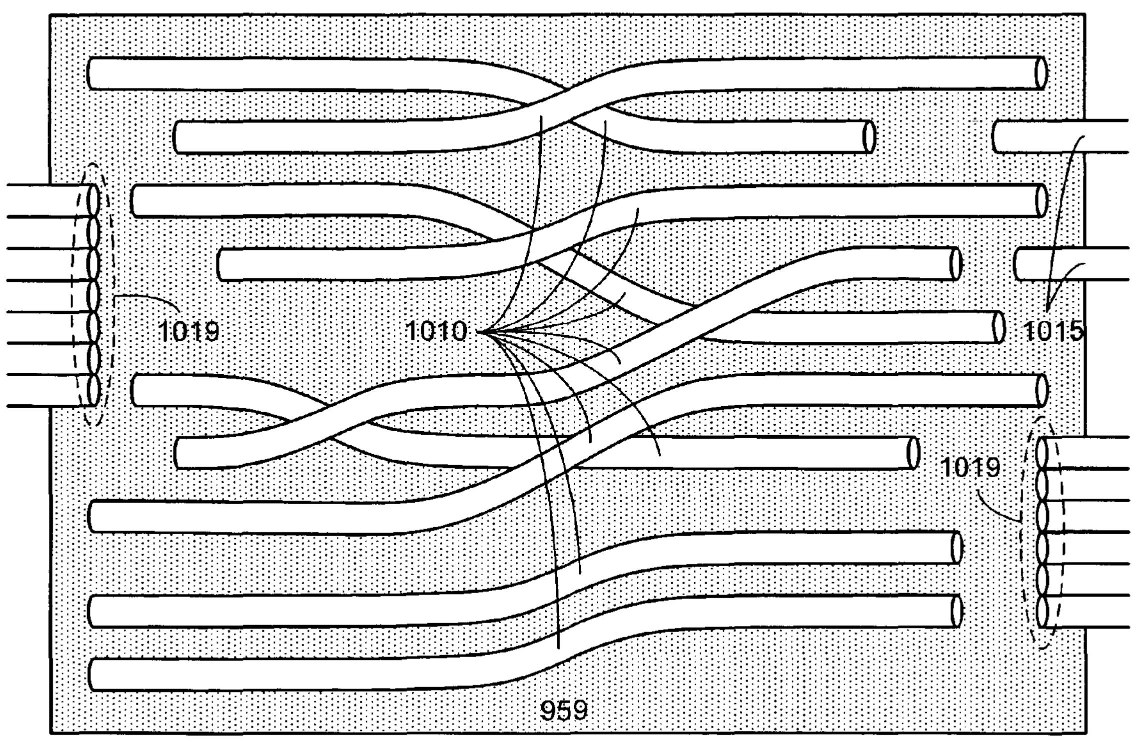

1019
1010
1015
1019
959

FIG. 10

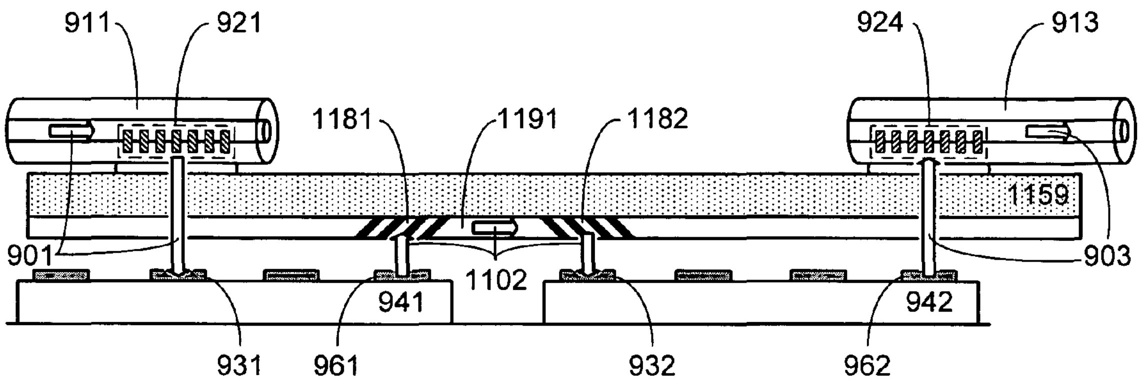
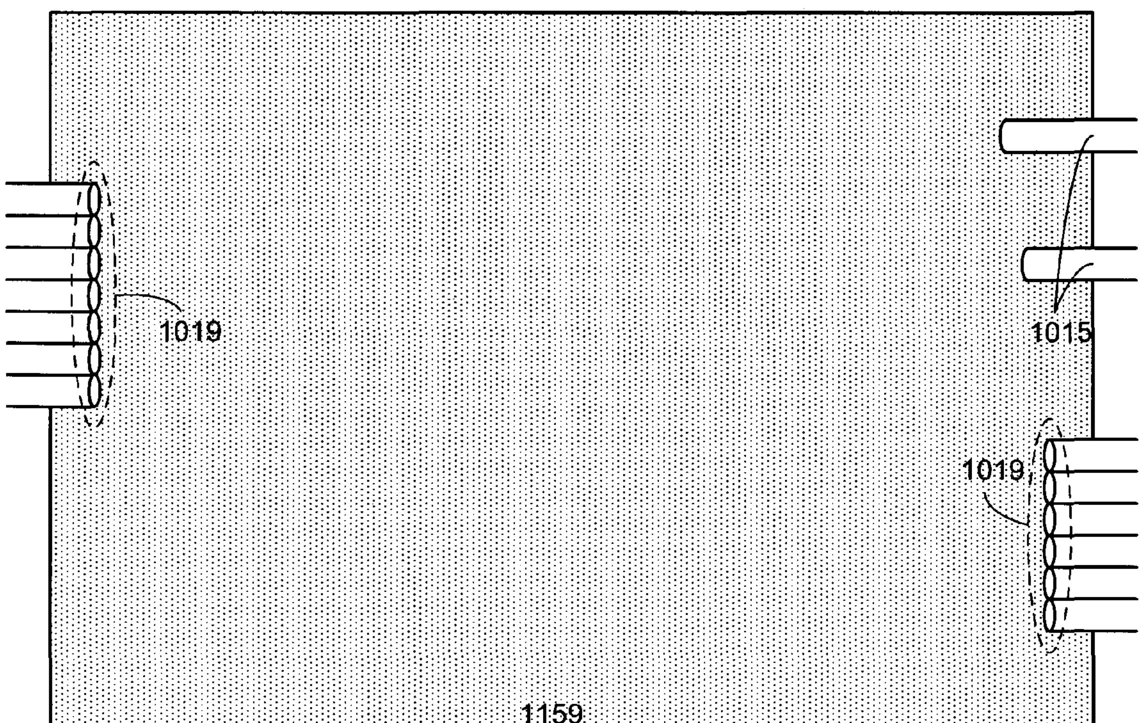

911
921
924
913
1181
1191
1182
1159
901
903
1102
941
942
931
961
932
962

FIG. 11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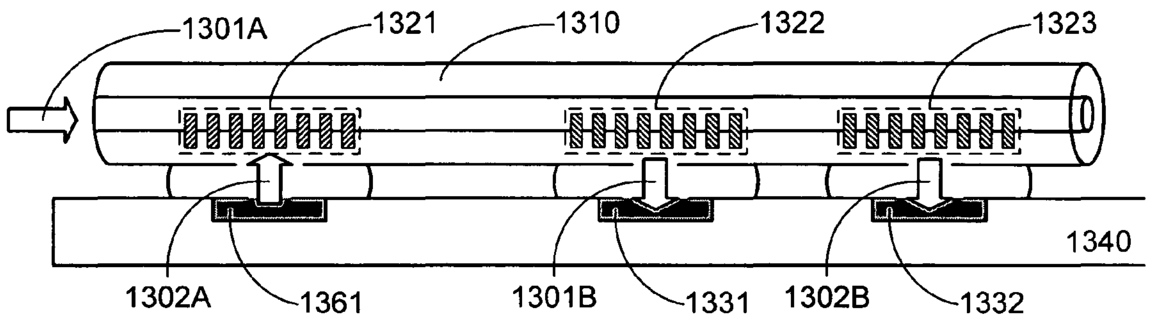
1015
1019
1159

FIG. 12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1310
1322
1323
1340
1302A
1361
1301B
1331
1302B
1332

FIG. 13

OPTICAL INTERCONNECTS IN MICROELECTRONICS BASED ON AZIMUTHALLY ASYMMETRIC LONG-PERIOD FIBER GRATING COUPLERS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to co-pending U.S. provisional application entitled, "Optical Interconnects in Microelectronics based on Azimuthally Azymmetric Long-Period Fiber Grating Couplers," having Ser. No. 60/605,860, filed Aug. 31, 2004, which is entirely incorporated herein by reference.

TECHNICAL FIELD

The present disclosure is generally related to optical fiber gratings and, more particularly, embodiments of the present disclosure are related to grating coupling for chip and/or wafer-level optical interconnects and methods of use.

BACKGROUND

There is a critical need for highly integrated wafer-level optical interconnections in microelectronics at the die-to-module/board level. Input/output (I/O) interconnections between die and board have traditionally been provided by metallic conductors. Electrical interconnects, however, have inherent limitations which include high noise, high drive powers, impedance matching requirements, tradeoff between data rate and distance, insufficient densities/data rates, and expensive redesign. Optical interconnects, on the other hand, have the potential for low noise, low drive power, high density, high data rates, simplified design and redesign. Due to the above performance limitations of electrical interconnects, not only have optical interconnects replaced electrical interconnects for long distance communications, but optical interconnects are also being developed for chip-to-chip I/O interconnections. Micro-optical devices and interconnects can potentially greatly enhance the performance of a micro-system by leveraging high-bandwidth, low-latency, cross-talk-resilient, and low-power communication networks. The projected off-chip communication speed for some chip I/O's is as high as 56.843 GHz at the 18-nm technology node. The introduction of optical I/O interconnection adds new constraints and new problems. Among these is the ability to fabricate prototype optically interconnected micro-systems and limited-production, application-specific, optically interconnected micro-systems.

SUMMARY

Systems and methods, including azimuthally asymmetric fiber grating are disclosed. A representative embodiment of a system, among others, includes an optical fiber including at least one azimuthally asymmetric fiber grating, and a device, wherein the azimuthally asymmetric fiber grating couples an optical signal frequency from the optical fiber to the device.

Another representative embodiment of a system, among others, includes an optical fiber including at least one azimuthally asymmetric fiber grating, and a device including at least one optical element, wherein at least one azimuthally asymmetric fiber grating is aligned with the optical element, and wherein the azimuthally asymmetric fiber grating couples a first optical frequency to the optical element.

A representative embodiment of a method, among others, includes aligning an interconnection plane with a device including at least one optical element, aligning an optical fiber including at least one azimuthally asymmetric fiber grating with the interconnection plane so that at least one azimuthally asymmetric fiber grating is aligned with the optical element, and bonding the optical fiber to the interconnection plane.

Another representative embodiment of a method, among others, includes aligning an optical fiber including at least one azimuthally asymmetric fiber grating with an interconnection plane so that, when the interconnection plane is aligned with a device including at least one optical element, at least one azimuthally asymmetric fiber grating is aligned with the optical element; bonding the optical fiber to the interconnection plane; and aligning the interconnection plane with the device so that the azimuthally asymmetric fiber grating is aligned with the optical element.

BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

FIG. **1**A is a graphical representation of light from an azimuthally asymmetric long-period fiber grating.

FIG. **1**B is a plot of light from an azimuthally asymmetric long-period fiber grating.

FIG. **2**A is a schematic representation of an embodiment of a fiber-to-chip coupling.

FIG. **2**B is a schematic representation of an embodiment of a chip-to-fiber coupling.

FIG. **3** is a schematic representation of an embodiment of a fiber-to-waveguide and/or waveguide-to-fiber coupling.

FIG. **4** is a schematic representation of an embodiment of a fiber-to-fiber coupling.

FIG. **5**A is a schematic representation of an embodiment of an intra-chip coupling.

FIG. **5**B is a schematic representation of an embodiment of an intra-chip fan-out coupling.

FIG. **6**A is a schematic representation of an embodiment of a fiber-ribbon-to-chip coupling.

FIG. **6**B is a schematic representation of an embodiment of a chip-to-fiber-ribbon coupling.

FIG. **7** is a schematic representation of an embodiment of an intra-chip fan-out coupling utilizing an optical interconnection plane.

FIG. **8**A is an illustration of the top view of an embodiment of an optical interconnection plane.

FIG. **8**B is an illustration of the top view of an embodiment of an optical interconnection plane including individual optical fibers for external connections.

FIG. **8**C is an illustration of the top view of an embodiment of an optical interconnection plane including fiber ribbon for external connections.

FIG. **8**D is an illustration of the top view of an embodiment of an optical interconnection plane with two interconnect layers.

FIG. **8**E is an illustration of the top view of an embodiment of an optical interconnection plane including individual optical fibers and fiber ribbon for external connections.

FIG. **9** illustrates an embodiment of a multi-chip coupling utilizing an optical interconnection plane 959 mounted on and/or above microelectronics chips 941 and 942. In this non-limiting embodiment, incoming signals 901 are guided by optical fibers 911. Azimuthally asymmetric LPFGs 921 in the fibers 911 diffract the signals **901** through an optical interconnection plane 959 and into optical receivers 931 on a microelectronics chip 941. In other embodiments, multiple out-coupling LPFGs 921 can be utilized to send the incoming signal 901 to multiple receivers 931. The LPFGs 921 can be optimized to divide transmitted signals 901 as discussed in U.S. Patent No. 6,832,023.

FIG. **10** is an illustration of the top view of an embodiment of an optical interconnection plane with optical fibers for a multi-chip coupling.

FIG. **11** is a schematic representation of an embodiment of a multi-chip coupling utilizing an optical interconnection plane with waveguides.

FIG. **12** is an illustration of the top view of an embodiment of an optical interconnection plane with waveguides for a multi-chip coupling.

FIG. **13** is a schematic representation of an embodiment of fiber-to-chip and intra-chip fan-out coupling with multiple optical signals transmitted at different frequencies.

DETAILED DESCRIPTION

The initial use of optical fibers by telecommunication companies confirmed that data transmission over optical fibers was a reliable and economical alternative to conventional methods. Increases in transmission rates, reduction in size, and consistency of manufacturing quality have driven the incorporation of optical networks to improve overall performance of electronic systems down to the chip and/or wafer level. Optical fibers can be used as optical interconnects between circuits on one or more chips. Coupling of optical signals between the fiber and the chip and/or wafer-level circuits can be accomplished by using optical gratings. Azimuthally asymmetric fiber gratings accomplish this by laterally coupling light through the side of the fiber.

Long-Period Fiber Gratings (LPFGs) are typically used as static band-rejection filters, static spectral shapers for high-power broadband sources, static gain equalizers for optical amplifiers, static filters for amplified spontaneous emission in erbium-doped fiber amplifiers, static wavelength stabilizers for pump diodes in optical amplifiers, sensors for refractive index, temperature, and strain, fiber optic polarizers, and all-optical switches. Embodiments of the present disclosure use LPFGs as couplers to couple light into and out of the fiber through the side of the fiber. This is enabled and made efficient by an azimuthally asymmetric grating in the fiber such as, but not limited to, carbon dioxide laser induced long-period fiber gratings. Embodiments of the LPFGs can be conveniently implemented using carbon dioxide laser pulses to produce intentional azimuthally varying refractive index profiles suitable for coupling applications. LPFGs can be implemented using other lasers based on the type of optical fiber used. Examples of these combinations can include, but are not limited to, ultraviolet and/or femtosecond-pulse lasers combined with polarization-maintaining fiber, D-shaped fiber, or specially doped single-mode fiber. Implementation of azimuthally varying gratings disposed in optical fibers is discussed in "Optical Fiber Gratings with Azimuthal Refractive Index Perturbation, Method of Fabrication, and Devices for Tuning, Attenuating, Switching, and Modulating Optical Signals," U.S. Pat. No. 6,832,023, which is hereby incorporated by reference. Azimuthally varying grating elements are formed via direct illumination of the fiber at a desired periodicity based on the wavelength of a selected transmission signal. The combination of period spacing between the grating elements and number of elements is chosen to optimize the coupling of the transmitted light in the region of the selected wavelength. While the following descriptions focus on LPFGs, it is to be understood that the present disclosure includes other in-fiber gratings such as, but not limited to, short-period fiber Bragg gratings, tilted gratings, superstructure gratings, and the like.

An advantage of using azimuthally asymmetric LPFGs for coupling is illustrated by the light patterns emerging from an azimuthally asymmetric LPFG, which are shown in FIG. **1**A and in FIG. **1**B. From the image in FIG. **1**A, it is evident that the intensity of the light is not constant around the circumference for a given radius (azimuthal variation). The plot in FIG. **1**B also indicates the azimuthal variation by showing the normalized intensity of the light in FIG. **1**A through the vertical center along the horizontal length. The intensity variation along the azimuthal direction is evident from the difference in heights between corresponding peaks in the positive and negative length regions of the plot. Efficient coupling into and out of the fiber can occur with the azimuthally asymmetric light variations produced by azimuthally asymmetric LPFGs.

LPFG devices use optical fibers that incorporate azimuthally asymmetric LPFGs for coupling light into and out of a fiber through the side of the fiber. The azimuthally asymmetric LPFGs can perform lateral coupling in the optical fiber. The present disclosure incorporates optical fibers with azimuthally asymmetric LPFGs to make LPFG optical interconnections in microelectronic applications including, but not limited to, intra-chip, chip-to-chip, intra-board, board-to-board, and fiber-to-fiber interconnections, and combinations thereof. LPFG optical interconnects include a combination of optical fibers and LPFG couplers disposed in those fibers. The LPFG couplers can stand alone to produce optical interconnections and/or can be integrated with other types of optical interconnects.

In addition to large-scale production of optical interconnections in microelectronics, the LPFG devices may be used for prototyping and production of optical interconnects in microelectronics. Due to the inherent flexibility of using one or more individual optical fibers incorporating fiber-grating couplers, it is possible to rapidly configure and/or reconfigure optically interconnected microelectronics systems. This flexibility can offer advantages in the design, development, and testing of optically interconnected microelectronics to be produced using other optical interconnect technologies. Embodiments of the devices can also produce limited-quantity application-specific optically interconnected microelectronics modules.

Embodiments of optical interconnects in microelectronics based on azimuthally asymmetric LPFG couplers are described below. It should be emphasized that the described embodiments are merely possible examples of implementations, and are set forth for a clear understanding of the principles of the present disclosure, and in no way limit the scope of this disclosure. While the following descriptions focus on LPFGs, it is to be understood that the present disclosure includes other in-fiber gratings such as, but not limited to, short-period fiber Bragg gratings.

FIG. **2**A illustrates an embodiment of a fiber-to-chip coupling. In this regard, an incoming optical signal **200**A is guided by an optical fiber **210**. In this non-limiting embodiment, an azimuthally asymmetric long-period fiber grating (LPFG) **220** in the fiber **210** diffracts the optical signal **200**B towards an optical receiver **230**, such as, but not limited to, a photodetector. The LPFG **220** is aligned with the optical receiver **230** such that the transmitted optical signal **200**B is detectable at the optical receiver **230**. The fiber **210** is mounted on a microelectronics chip **240** containing the optical receiver **230**. Preparation of the fiber **210** for mounting can be used to improve signal transmission. For example, the fiber can be altered in a manner including, but not limited to, shaping the mounting surface of the fiber **210** (e.g., flattening, making planar, and making D-shaped) to improve the coupling between the LPFG **220** and the optical receiver **230**. An index-matching compound **250** (e.g., index-matching optical adhesive, epoxy, and gel) can be used to bond the fiber **210** to the chip **240**. Utilizing an index-matching compound **250** with a refractive index similar to the cladding of the optical fiber **210** and the optical receiver **230** enhances coupling of the LPFG **220** and the optical receiver **230**. In one non-limiting embodiment, a compound **250** with a refractive index approximately equal to the cladding of the optical fiber can be used to maximize lateral signal transmission out of the fiber. The use of index-matching compounds to maximize optical coupling is well understood by one skilled in the art. For the embodiment shown, the LPFG **220** is optimized for maximum transmission efficiency. The coupling efficiency can be from about 1 to 100% and can be optimized for particular embodiments.

FIG. **2**B illustrates an embodiment of a chip-to-fiber coupling. In this depiction, an optical transmitter or light source **260** (e.g., laser and light-emitting diode) mounted on a microelectronics chip **240** emits an optical signal **270**A. An azimuthally asymmetric LPFG **220** is aligned with the optical transmitter **260** such that the transmitted optical signal **270**A is detectable at the LPFG **220**. The LPFG **220** in the fiber **210** diffracts the optical signal **270**B into an outgoing guided mode along the fiber **210**. Appropriate preparation, positioning, index-matching, and bonding of the fiber **210** to the chip **240** can be used to optimize transmission of the outgoing optical signal **270**B.

FIG. **3** illustrates an embodiment of a fiber-to-waveguide and/or waveguide-to-fiber coupling. In this regard, an incoming optical signal **300**A is guided by an optical fiber **310**. In this non-limiting embodiment, an azimuthally asymmetric LPFG **320** in the fiber **310** diffracts the optical signal **300**B towards a waveguide optical element **380** (e.g., a diffractive and/or reflective element, such as, but not limited to, a volume grating, a surface-relief grating, a total internal reflection (TIR) element, or a metallic mirror). The fiber **310** is mounted on a microelectronics chip **340** containing the waveguide optical element **380**. The element **380** diffracts and/or reflects the optical signal **300**B into a guided mode in a waveguide **390** where the optical signal **300**C is routed on the chip **340**. Coupling efficiency between the LPFG **320** and the waveguide optical element **380** is highest when the refractive index of the waveguide **390** is close to the cladding of the optical fiber **310**. The types of waveguides **390** can include, but are not limited to, polymer or glass-based channel (or combinations thereof), ridge, or diffused (or combinations thereof) waveguides.

In addition, an outgoing signal **300**C can be guided on the chip **340** by a waveguide **390** to a waveguide optical element **380**. The element **380** diffracts or reflects the optical signal **300**B into an optical fiber **310** where it is diffracted by a LPFG **320** along the fiber **310**. The optical fiber **310** guides the outgoing signal **300**A toward its destination. Appropriate preparation, positioning, index-matching, and bonding of the fiber **310** to the chip **340** can optimize signal transmission.

In another embodiment that is not depicted, an azimuthally asymmetric LPFG in an optical fiber is aligned with a waveguide for coupling an optical signal without use of a waveguide optical element. An index-matching compound is applied between the optical fiber at the LPFG and the waveguide to enhance coupling. In this embodiment, an optical signal is guided by the optical fiber and defracted into the waveguide by the azimuthally asymmetric LPFG.

FIG. **4** illustrates an embodiment of a fiber-to-fiber coupling. In this depiction, an incoming optical signal **400**A is guided by an optical fiber **411**. In this non-limiting embodiment, an azimuthally asymmetric LPFG **421** in the fiber **411** diffracts the signal **400**B towards a second optical fiber **412**, which is acting as an optical element. A second LPFG **422** diffracts the optical signal **400**B into a guided mode in the second fiber **412**, where the optical signal **400**C is guided toward its destination. Appropriate preparation, positioning, index-matching, and bonding of the fibers **411** and **412** can optimize signal transmission.

In addition, an outgoing signal **400**C can be guided along the second optical fiber **412** to the azimuthally asymmetric LPFG **422**. The LPFG **422**, which is acting as an optical element, diffracts the optical signal **400**B into the first optical fiber **411** where it is diffracted by a LPFG **421** along the first fiber **411**. This optical fiber **411** guides the outgoing signal **400**A toward its destination.

FIG. **5**A illustrates an embodiment of an intra-chip coupling using long-period fiber gratings. In this non-limiting embodiment, an optical transmitter or light source **560** emits an optical signal **500**A. An azimuthally asymmetric LPFG **521** diffracts the signal **500**A into a guided mode along the fiber **510**. A second azimuthally asymmetric LPFG **522** in the fiber **510** diffracts the signal **500**B into an optical receiver **530** on the microelectronics chip **540**.

FIG. **5**B illustrates an embodiment of an intra-chip fan-out coupling where an optical transmitter **560** is linked to multiple receivers **531** and **532**. In this embodiment, an optical transmitter **560** on a microelectronics chip **540** emits an optical signal **500**A. An azimuthally asymmetric LPFG **521** diffracts the signal **500**A into a guided mode along the fiber **510**. A second and a third LPFG **522** and **523**, located along the fiber **510**, diffract portions of the optical signal **500**A into optical receivers **531** and **532**. For the embodiment shown, the first out-coupling LPFG **522** diffracts a portion of the optical signal **500**B into the first optical receiver **531**. The remaining portion of the optical signal **500**C continues along the fiber and is diffracted by the second out-coupling LPFG **523** into the second optical receiver **532**. Other embodiments of intra-chip fan-out coupling can include, but are not limited to, combinations using one or more optical transmitter/LPFG pairs and/or one or more out-coupling LPFG/optical receiver pairs. Out-coupling LPFGs can be optimized to divide transmitted signals as discussed in U.S. Pat. No. 6,832,023.

Intra-chip coupling and intra-chip fan-out coupling can also be implemented using waveguides and waveguide optical elements as discussed in relation to FIG. **3**. Again, out-coupling LPFGs can be optimized to divide transmitted signals as discussed in U.S. Pat. No. 6,832,023.

FIG. **6**A illustrates an embodiment of a fiber-ribbon-to-chip coupling. In this non-limiting embodiment, an incoming optical signal **601**A is guided along an optical fiber **611** in a fiber ribbon including multiple fibers **611**, **612**, **613**, and **614**. The number of fibers included in a ribbon can vary based on the application (e.g., 2 to 82). An azimuthally asymmetric LPFG **621** in the fiber **611** diffracts the optical signal **601**B towards an optical receiver **631** mounted on a microelectronics chip **640**. Additional incoming signals **602**A, **603**A, and **604**A are routed along their respective fibers **612**, **613**, and **614** to LPFGs that diffract the signals toward separate optical receivers mounted on the microelectronics chip **640**. Appropriate preparation, positioning, index-matching, and bonding during mounting of the fiber ribbon to the chip **640** can be used to optimize signal transmission.

FIG. **6**B illustrates an embodiment of a chip-to-fiber-ribbon coupling. In this embodiment, an optical transmitter **661** emits an optical signal **671**A into an optical fiber **611** in a fiber ribbon including multiple fibers **611**, **612**, **613**, and **614**. The number of fibers included in a ribbon can vary based on the application. An azimuthally asymmetric LPFG **621** in the fiber **611** diffracts the optical signal **671**B into a guided mode along the optical fiber **611**. Additional outgoing signals **672**B, **673**B, and **674**B are routed along their respective fibers **612**, **613**, and **614** after being emitted by optical transmitters mounted on the chip **640** and diffracted by LPFGs in the fibers **612**, **613**, and **614** of the fiber ribbon. The guided signals **671**B, **672**B, **673**B, and **674**B are outgoing from the fiber ribbon.

Coupling between chip and fiber ribbon can also be implemented using waveguides and waveguide optical elements for transmission of incoming and outgoing signals as discussed in relation to FIG. **3**. Other possible embodiments can also include configurations where both incoming and outgoing signals are sent on separate fibers and/or the same fiber of a fiber ribbon.

FIG. **7** illustrates an embodiment of an intra-chip fan-out coupling utilizing an optical interconnection plane **759** mounted on and/or above a microelectronics chip **740**. Signal routing can be provided by optical fibers **710** mounted on the optical interconnection plane **759**. Signal transmission through the optical interconnection plane **759** can be accomplished by, but is not limited to, using wavelengths of light transparent to the substrate material or physically creating paths, vias, or through-holes for the light such as, but not limited to, metallized reflective hollows, optical dielectrics, photonic crystal waveguides, optical fibers, and combinations thereof.

In this non-limiting embodiment, an optical transmitter **760** on a microelectronics chip **740** emits an optical signal **700**A. The optical signal **700**A passes through the optical interconnection plane **759** and into the fiber **710** where an azimuthally asymmetric LPFG **721** diffracts the signal **700**A into a guided mode along the fiber **710**. A second and a third LPFG **722** and **723**, located along the fiber **710**, diffract portions of the optical signal **700**A through the optical interconnection plane **759** and into optical receivers **731** and **732**. For the embodiment shown, the first out-coupling LPFG **722** diffracts a portion of the optical signal **700**B through the optical interconnection plane **759** and into the first optical receiver **731**. The remaining portion of the optical signal **700**C continues along the fiber and is diffracted by the second out-coupling LPFG **723** through the optical interconnection plane **759** and into the second optical receiver **732**.

In addition, embodiments of intra-chip fan-out coupling on an optical interconnection plane **759** can include, but are not limited to, combinations using one or more optical transmitter/LPFG pairs and/or one or more out-coupling LPFG/optical receiver pairs. Intra-chip coupling and intra-chip fan-out coupling on an optical interconnection plane **759** can also be implemented using waveguides and waveguide optical elements as discussed in relation to FIG. **3**. The types of waveguides **390** can include, but are not limited to, polymer or glass-based channel (or combinations thereof), ridge, or diffused (or combinations thereof) waveguides. Out-coupling LPFGs can be optimized to divide transmitted signals as discussed in U.S. Pat. No. 6,832,023.

Optical interconnection planes **759** also allow for preassembly of optical fibers **710** for intra-chip coupling prior to mounting on and/or above the microelectronics chip **740**. This allows for separation of the optical and microelectronic production processes. Additionally, preassembly allows for separate testing of intra-chip coupling and intra-chip fan-out coupling on the interconnection plane **759** prior to and/or after mounting and testing of the microelectronics chip **740**.

FIG. **8**A illustrates an embodiment of a top view of an optical interconnection plane **759** mounted above the microelectronics chip **740** (FIG. **7**). In this non-limiting embodiment, a number of optical fibers **810** mounted to the optical interconnection plane **759** provide routing of signals between optical elements, such as, but not limited to, optical receivers, optical transmitters, diffractive elements, and reflective elements, on the microelectronics chip **740**. LPFGs in the fibers **810** are aligned with the optical elements as described in relation to FIG. **7**. Using the flexibility of the fibers **810**, it is possible for the fibers **810** to cross over each other, as shown, to provide routing between optical elements located at different positions across the chip.

FIG. **8**B depicts a variation of the embodiment of a top view of an optical interconnection plane **759** described in relation to FIG. **8**A. In this embodiment, individual optical fibers **815** provide external connections for transmitting incoming and/or outgoing signals. Another embodiment of a top view of an optical interconnection plane **759** is shown in FIG. **8**C, where a fiber ribbon **819** provides external connections for transmitting incoming and/or outgoing signals.

FIG. **8**D illustrates an embodiment of a top view of an optical interconnection plane **759** mounted above a microelectronics chip **740**. In this non-limiting embodiment, two layers of fibers are used to route signals between optical elements on the microelectronics chip **740**. The fibers **811** in the first layer are shown vertically routed between optical elements at various locations beneath the fibers **811**. The fibers **812** in the second layer are shown horizontally routed between optical elements at various locations beneath the fibers **812**. The horizontally oriented fibers **812** are shown passing over the first layer of fibers **811** to form the second layer.

FIG. **8**E illustrates a variation of the embodiment of a top view of an optical interconnection plane **759** described in relation to FIG. **8**D. In this embodiment, optical fibers **813** route signals vertically and horizontally in a single layer. Individual optical fibers **815** and fiber ribbon **819** provide external connections for transmitting incoming and/or outgoing signals.

Other embodiments can include, but are not limited to, optical fibers oriented in one or more directions, fibers crossing over one or more fibers, fibers routed in one or more layers, one or more individual fibers and/or one or more fiber ribbons for external connections, and combinations thereof.

FIG. **9** illustrates an embodiment of a multi-chip coupling utilizing an optical interconnection plane **959** mounted on and/or above microelectronics chips **941** and **942**. In this non-limiting embodiment, incoming signals **901** are guided by optical fibers **911**. Azimuthally asymmetric LPFGs **921** in the fibers **911** diffract the signals **901** through an optical interconnection plane **959** and into optical receivers **931** on a microelectronics chip **941**. In other embodiments, multiple out-coupling LPFGs **921** can be utilized to send the incoming signal **901** to multiple receivers **931**. The LPFGs **921** can be optimized to divide transmitted signals **901** as discussed in U.S. Pat. No. 6,832,023.

Optical transmitters **961** on a microelectronics chip **941** emit optical signals **902**. The optical signals **902** pass through an optical interconnection plane **959** and into fibers **912** where azimuthally asymmetric LPFGs **922** diffract the signal **902** into a guided mode along the fibers **912**. One or more LPFGs **923** located along the fibers **912** diffract the optical signals **902** through the optical interconnection plane **959** and into optical receivers **932** on a separate microelectronics chip **942**. Other embodiments of multi-chip coupling can include, but are not limited to, combinations using one or more optical transmitter **961**/LPFG **922** pairs and/or one or more out-coupling LPFG **923**/optical receiver **932** pairs. Out-coupling LPFGs **923** can be optimized to divide transmitted signals as discussed in U.S. Pat. No. 6,832,023.

Optical transmitters **962** mounted on a microelectronics chip **942** emit outgoing signals **903** through an optical interconnection plane **959** and into optical fibers **913**. Azimuthally asymmetric LPFGs **924** diffract the optical signals **903** into an outgoing guided mode along the fiber **913**.

Optical interconnection planes **959** also allow for preassembly of optical fibers **911**, **912**, and **193** for coupling prior to mounting on and/or above the microelectronics chips **941** and **942**. This allows for separation of the optical and microelectronic production processes. Additionally, preassembly allows for separate testing of coupling on the interconnection plane **959** prior to and/or after mounting and testing of the microelectronics chips **941** and **942**.

FIG. **10** illustrates an embodiment of a top view of an optical interconnection plane **959** mounted above microelectronics chips **941** and **942** (FIG. **9**). In this non-limiting embodiment, a number of optical fibers **1010** mounted to the optical interconnection plane **959** provide routing of signals between optical elements, such as, but not limited to, optical receivers, optical transmitters, diffractive elements, and reflective elements, on the microelectronics chips **941** and **942**. The LPFGs in the fibers **1010** are aligned with optical elements on the chips **941** and **942** to provide routing of signals between chips and/or between elements on the same chip. Using the flexibility of the fibers **1010**, it is possible for the fibers **1010** to cross over each other, as shown, to provide routing between optical elements located at different positions across the chip. Individual optical fibers **1015** and/or fiber ribbons **1019** provide external connections for transmitting incoming and/or outgoing signals to one and/or more chips.

FIG. **11** illustrates an embodiment of a multi-chip coupling utilizing an optical interconnection plane **1159** with waveguides **1191** mounted on and/or above microelectronics chips **941** and **942**. The types of waveguides **390** can include, but are not limited to, polymer, or glass-based channel (or combinations thereof), ridge, or diffused (or combinations thereof) waveguides. As described in relation to FIG. **9**, incoming signals **901** are guided by optical fibers **911**. The azimuthally asymmetric LPFGs **921** in the fibers **911** diffract the signals **901** through an optical interconnection plane **1159** and into optical receivers **931** on a microelectronics chip **941**.

In this non-limiting embodiment, optical transmitters **961** on a microelectronics chip **941** emit optical signals **1102**. The optical signals **1102** are diffracted and/or reflected by waveguide optical elements **1181** into guided modes in waveguides **1191** on the optical interconnection plane **1159**. The signals **1102** are routed to other waveguide optical elements **1182** that diffract and/or reflect into optical receivers **932** on a separate microelectronics chip **942**.

As described in relation to FIG. **9**, the optical transmitters **962** mounted on a microelectronics chip **942** emit outgoing signals **903** through an optical interconnection plane **1159** and into the optical fibers **913**. The azimuthally asymmetric LPFGs **924** diffract the optical signals **903** into an outgoing guided mode along the fiber **913**.

FIG. **12** illustrates an embodiment of a top view of an optical interconnection plane **1159** with waveguides mounted above microelectronics chips **941** and **942**. In this non-limiting embodiment, optical waveguides provide routing of signals between optical elements, such as, but not limited to, optical receivers, optical transmitters, diffractive elements, and reflective elements, on the microelectronics chips **941** and **942**. Waveguide optical elements, such as, but not limited to, diffractive and/or reflective elements are aligned with optical elements on the chips **941** and **942** to provide routing of signals between chips and/or between elements on the same chip. Individual optical fibers **1015** and/or fiber ribbons **1019** provide external connections for transmitting incoming and/or outgoing signals to one and/or more chips.

In another embodiment that is not depicted, combinations of optical fibers and/or waveguides, as depicted in FIGS. **9** and **11**, can be used for routing of signals between optical elements on the same or different chips. A waveguide can also be used to route a signal from an optical fiber to an optical element on a chip or to another optical fiber.

The embodiments illustrated above can be expanded to include transmission of multiple optical signals at different frequencies through a single optical fiber. The combination of period spacing between the grating elements and number of elements utilized in a LPFG optimizes the coupling of the transmitted signal at a selected wavelength. This allows a LPFG to couple with one optical signal transmitted at the corresponding frequency, while allowing signals at other frequencies to continue through the optical fiber.

FIG. **13** illustrates an embodiment of fiber-to-chip and intra-chip fan-out coupling with multiple optical signals transmitted at different frequencies. In this embodiment, an incoming optical signal **1301**A at a first signal frequency is guided by an optical fiber **1310**. A first LFPG **1321**, optimized for a second optical signal frequency, is aligned with an optical transmitter **1361** on the microelectronics chip **1340**. The optical transmitter **1361** emits an optical signal **1302**A at the second signal frequency. The first LPFG **1321** in the fiber **1310** diffracts the optical signal **1302**A into an outgoing guided mode along the fiber towards the second and third LFPGs **1322** and **1323**, while allowing the first signal **1301**A to continue along the fiber. The second LFPG **1322** is optimized for the first optical signal frequency and aligned with a first optical receiver **1331** on the microelectronics chip **1340**. The second LPFG **1322** in the fiber **1310** diffracts the optical signal **1301**B at the first frequency towards the first optical receiver **1331**, while allowing the signal **1302**A at the second frequency to continue along the fiber **1310**. The third LFPG **1323** is optimized for the second optical signal frequency and aligned with a second optical receiver **1332** on the microelectronics chip **1340**. The third LPFG **1323** diffracts the optical signal **1302**B at the second frequency towards the second optical receiver **1332**. Other embodiments of intra-chip fan-out coupling can include, but are not limited to, combinations using one or more optical transmitter/LPFG pairs and/or one or more out-coupling LPFG/optical receiver pairs. Likewise, other embodiments of fiber-to-chip coupling can include, but are not limited to, optical transmitters, diffractive elements, reflective elements, and waveguides.

Optical interconnect planes can be utilized for mounting optical fibers **1310** for transmission of optical signals at multiple frequencies as discussed for FIG. **7**. In addition, multiple microelectronic chips can be coupled using optical fibers suitable for transmission of optical signals at multiple frequencies, with or without an interconnect plane, as illustrated in FIGS. **9** and **11**.

It should be emphasized that the above-described embodiments of the present disclosure are merely possible examples of implementations, and are merely set forth for a clear understanding of the principles of the disclosure. Many variations and modifications may be made to the above-described embodiments. For example, a plurality of optical fiber and/or waveguide distributions can be included for routing signals between optical elements, such as, but not limited to, optical receivers, optical transmitters, diffractive elements, and reflective elements, on one or more microelectronics chips and/or connections external to the chips. Likewise, multi-chip coupling can be accomplished without the use of an interconnect plane. In addition, a plurality of in-fiber azimuthally asymmetric grating designs, such as, but not limited to, LPFG and short-period fiber Bragg gratings, can be utilized to couple multiple optical frequencies in a single optical fiber. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

Therefore, the following is claimed:

1. A system comprising:

a microelectronic chip structure including:

an optical fiber including an azimuthally asymmetric fiber grating, wherein the azimuthally asymmetric fiber grating is selected from one of: an azimuthally asymmetric long-period fiber grating and an azimuthally asymmetric short-period fiber Bragg grating; and

a microelectronic chip including at least one optical element, wherein the azimuthally asymmetric fiber grating is adjacent the optical element, wherein the azimuthally asymmetric fiber grating couples a first optical signal frequency to the optical element, wherein the optical element is selected from one of: an optical receiver, an optical transmitter, a diffractive element, and a reflective element.

2. The system of claim **1**, wherein the optical fiber includes a second azimuthally asymmetric fiber grating, wherein the microelectronic chip includes at least a second optical element, wherein the second azimuthally asymmetric fiber grating is adjacent the second optical element, and wherein the second azimuthally asymmetric fiber grating couples a second optical signal frequency to the second optical element.

3. The system of claim **1**, wherein the optical fiber includes a second azimuthally asymmetric fiber grating, wherein a second device includes at least one optical element, wherein the optical fiber is disposed adjacent to the second device so that the second azimuthally asymmetric fiber grating is aligned with the optical element on the second device.

4. The system of claim **3**, wherein the optical fiber is disposed adjacent to the second device.

5. The system of claim **1**, wherein the optical element is optically connected with a waveguide that includes optical waveguide elements separated by a length of the waveguide.

6. The system of claim **5**, wherein the waveguide optical element selected from one of: a diffractive element and a reflective element.

7. The system of claim **1**, wherein the azimuthally asymmetric fiber grating is an azimuthally asymmetric long-period fiber grating.

8. The system of claim **1**, wherein the azimuthally asymmetric fiber grating is an azimuthally asymmetric short-period fiber Bragg grating.

9. A system comprising:

a microelectronic chip structure including:

an optical fiber including at least one azimuthally asymmetric fiber grating; and

a microelectronic chip including at least one optical element, wherein the at least one azimuthally asymmetric fiber grating is aligned with the optical element, and wherein the azimuthally asymmetric fiber grating couples a first optical frequency to the optical element.

10. The system of claim **9**, wherein the azimuthally asymmetric fiber grating is an azimuthally asymmetric long-period fiber grating.

11. The system of claim **9**, wherein the azimuthally asymmetric fiber grating is an azimuthally asymmetric short-period fiber Bragg grating.

12. The system of claim **9**, wherein the optical element is selected from one of: an optical receiver, an optical transmitter, a diffractive element, and a reflective element.

13. The system of claim **9**, wherein a shape of the optical fiber is selected from one of: a D-shaped and a flattened shape.

14. The system of claim **9**, wherein the device is a second optical fiber including at least one azimuthally asymmetric fiber grating.

15. The system of claim **9**, wherein the optical fiber is disposed on an interconnection plane, wherein the interconnection plane is adjacent the microelectronic chip.

16. The system of claim **15**, wherein the interconnection plane includes at least one waveguide for routing optical signals between optical elements on the device.

17. The system of claim **9**, wherein an index-matching compound is disposed between the optical fiber and an interconnection plane, wherein the interconnection plane is adjacent the microelectronic chip, and wherein the index-matching compound is adjacent the azimuthally asymmetric fiber grating and the optical element.

18. The system of claim **9**, wherein the optical fiber includes at least two azimuthally asymmetric fiber gratings.

19. The system of claim **18**, wherein the microelectronic chip includes at least a second optical element, wherein the second azimuthally asymmetric fiber grating is aligned with the second optical element on the microelectronic chip.

20. The system of claim **18**, wherein at least a second device includes at least one optical element, wherein the second azimuthally asymmetric fiber grating is aligned with the optical element on the second device.

21. The system of claim **20**, wherein the optical fiber is disposed on at least the first and the second microelectronic chips.

22. The system of claim **20**, wherein the optical fiber is disposed on an interconnection plane, wherein the interconnection plane is aligned with at least the first and the second microelectronic chip.

23. The system of claim 22, wherein the interconnection plane includes at least one waveguide for routing optical signals between optical elements on the first and the second devices.

24. The system of claim 18, wherein the first azimuthally asymmetric fiber grating couples a first optical signal frequency and the second azimuthally asymmetric fiber grating couples a second optical signal frequency.

25. The system of claim 18, wherein the optical fiber is one of at least two optical fibers forming a fiber ribbon.

26. The system of claim 25, wherein at least a second optical fiber of the fiber ribbon includes at least one azimuthally asymmetric fiber grating, wherein the microelectronic chip includes at least a second optical element, wherein the azimuthally asymmetric fiber grating of the second optical fiber is aligned with the second optical element.

27. The system of claim 26, wherein the fiber ribbon is disposed on an interconnection plane, wherein the interconnection plane is aligned with the microelectronic chip.

28. A method comprising:

aligning an interconnection plane with a first microelectronic chip including at least one optical element;

aligning an optical fiber including at least one azimuthally asymmetric fiber grating with the interconnection plane so that at least one azimuthally asymmetric fiber grating is aligned with the optical element; and

bonding the optical fiber to the interconnection plane.

29. The method of claim 28, wherein the interconnection plane is aligned with at least the first microelectronic chip and a second microelectronic chip, wherein each of the first microelectronic chip and the second microelectronic chip include at least one optical element.

30. The method of claim 29, wherein the optical fiber is further aligned with the interconnection plane so that a second azimuthally asymmetric fiber grating included in the optical fiber is aligned with the optical element on the second microelectronic chip.

31. A method comprising:

aligning an optical fiber including at least one azimuthally asymmetric fiber grating with an interconnection plane so that, when the interconnection plane is aligned with a microelectronic chip including at least one optical element, at least one azimuthally asymmetric fiber grating is aligned with the optical element;

bonding the optical fiber to the interconnection plane; and

aligning the interconnection plane with the microelectronic chip so that the azimuthally asymmetric fiber grating is aligned with the optical element.

32. The method of claim 31, wherein the interconnection plane is aligned with at least the first microelectronic chip and a second microelectronic chip, wherein each of the first microelectronic chip and the second microelectronic chip include at least one optical element.

33. The method of claim 32, wherein the optical fiber is further aligned with the interconnection plane so that, when the interconnect plane is aligned with the first microelectronic chip and a second microelectronic chip, a second azimuthally asymmetric fiber grating included in the optical fiber is aligned with the optical element on the second microelectronic chip.

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