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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
14 April 2022 (14.04.2022)

WIPO | PCT

(10) International Publication Number
WO 2022/076993 A1

(51) International Patent Classification:

G02F 1/377 (2006.01)	*G02B 6/293* (2006.01)
G02F 1/35 (2006.01)	*G02F 1/39* (2006.01)
G02F 1/37 (2006.01)	*G02F 1/21* (2006.01)
G02F 1/365 (2006.01)	*G02B 6/12* (2006.01)

(21) International Application Number:
PCT/US2021/071725

(22) International Filing Date:
05 October 2021 (05.10.2021)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

63/088,220	06 October 2020 (06.10.2020)	US
63/201,661	07 May 2021 (07.05.2021)	US
63/201,664	07 May 2021 (07.05.2021)	US

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(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, IT, 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, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

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

Declarations under Rule 4.17:
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) Title: NONLINEAR OPTICAL WAVEGUIDE STRUCTURES FOR LIGHT GENERATION AND CONVERSION

(57) Abstract: An optical waveguide structure (100) comprising a nonlinear optical waveguide (102), a central region (114), a first side region (116), and a second side region (118). The central region (114) is located within the nonlinear optical waveguide (102), wherein the central reg1.on (114) comprises a non1inear optical material (104). The first side region (116) is on a first side (120) of the central region (114) and the second side region (118) is on a second side of the central region (114). The nonlinear optical material (104) comprising the central region (114) has a first nonlinear coefficient (124) that is larger than a second nonlinear coefficient (126) of a second material (119) comprising the first side region (116) and the second side region (118).

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NONLINEAR OPTICAL WAVEGUIDE STRUCTURES FOR LIGHT GENERATION AND CONVERSION

RELATED PROVISIONAL APPLICATION

This application is related to and claims the benefit of priority of provisional U.S. Patent Application Serial No. 63/088,220, entitled "Directional Phase Matching (DPM) Optical Waveguide", filed on October 6, 2020, provisional U.S. Patent Application Serial No. 63/201,661, entitled "Directional Phase Matching Optical Waveguide", filed on May 7, 2021, and provisional U.S. Patent Application Serial No. 63/201,664, entitled "Nonlinear Optical Waveguide Structures for Light Generation and Conversion", filed on May 7, 2021, all of which are hereby incorporated by reference.

BACKGROUND INFORMATION

Field:

The present disclosure relates generally to optical waveguide structures and, in particular, to optical waveguides with nonlinear optical materials.

Background:

Optical waveguides are physical structures that guide electromagnetic waves in an optical spectrum. Optical waveguides can be used as components in integrated optical circuits. With respect to quantum communications and processing, nonlinear optical material structures can be used to create photon transmitters, repeaters, and other quantum devices for communications. Nonlinear optical structures can be used to change the

light passing through them depending on factors such as orientation, temperature, wavelength of light, polarization of light, and other factors.

For example, a waveguide with light of a blue wavelength passing through the waveguide can generate one or more photons of light that has a longer wavelength, such as green or red, and a correspondingly lower photon energy. This type of conversion can be performed using waveguides that incorporate a nonlinear optical material having a second order or third order nonlinear optical susceptibility.

Current waveguides and structures that implement nonlinear optical processes are not as efficient as desired. Therefore, it would be desirable to have a method and apparatus that take into account at least some of the issues discussed above, as well as other possible issues. For example, it would be desirable to have a method and apparatus that overcome a technical problem with increasing the efficiency of nonlinear optical processes using optical waveguides with nonlinear optical materials.

SUMMARY

An embodiment of the present disclosure provides an optical waveguide structure comprising a nonlinear optical waveguide, a central region, a first side region, and a second side region. The central region is located within the nonlinear optical waveguide, wherein the central region comprises a nonlinear optical material. The first side region is on a first side of the central region and the second side region is on a second side of the central region. The nonlinear optical material comprising the central region has a first nonlinear coefficient that is larger than a second nonlinear coefficient of a second material comprising the first side region and the second side region.

Another embodiment of the present disclosure provides method for moving a light through a nonlinear optical waveguide structure. A light at a pump wavelength is input into the nonlinear optical waveguide structure having a central region within a nonlinear optical waveguide in the nonlinear optical waveguide structure; a first side region of a first side of the central region; and a second side region on a second side of the central region. The central region comprises a nonlinear optical material and the central region has a first nonlinear coefficient that is larger than a second nonlinear coefficient of the first side region and the second side region. The light at the pump wavelength is propagated along a path in the optical waveguide structure, wherein light generation occurs in the nonlinear optical waveguide.

The features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in

which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

Figure 1 is an illustration of a block diagram of an optical waveguide structure in accordance with an illustrative embodiment;

Figure 2 is an illustration of a block diagram of a configuration for an optical waveguide structure in accordance with an illustrative embodiment;

Figure 3 is an illustration of a cross-sectional view of a nonlinear optical waveguide in an optical waveguide structure in accordance with an illustrative embodiment;

Figure 4 is an illustration of field profiles in a nonlinear optical waveguide in accordance with an illustrative embodiment;

Figure 5, an illustration of field profiles in central region of a nonlinear optical waveguide as depicted in accordance with an illustrative embodiment.

Figure 6 is an illustration of a graph of an optical field overlap factor for different configurations of nonlinear optical waveguides in accordance with an illustrative embodiment;

Figure 7 is an illustration of a cross-sectional view of an optical waveguide structure with electrodes in accordance with an illustrative embodiment;

Figure 8 is an illustration of a cross-sectional view of an optical waveguide structure in accordance with an illustrative embodiment;

Figure 9 is another illustration of a cross-sectional view of an optical waveguide structure with a two-core region in accordance with an illustrative embodiment;

Figure 10 is yet another illustration of a cross-sectional view of an optical waveguide structure with a two-core region in accordance with an illustrative embodiment;

Figure 11 is an illustration of a cross-sectional view of an optical waveguide structure with merged core regions that form a multimode interference coupler in accordance with an illustrative embodiment;

Figure 12 is yet another illustration of a cross-sectional view of an optical waveguide structure with merged core regions that form a multimode interference coupler in accordance with an illustrative embodiment;

Figure 13 is an illustration of a cross-sectional view of an optical waveguide structure in accordance with an illustrative embodiment;

Figure 14 is an illustration of an optical waveguide structure in accordance with an illustrative embodiment;

Figure 15 is an illustration of an optical waveguide structure in accordance with an illustrative embodiment;

Figure 16 is an illustration of a flowchart of a process for moving light through an optical waveguide structure in accordance with an illustrative embodiment; and

Figure 17 is an illustration of a block diagram of a product management system in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

The illustrative embodiments recognize and take into account one or more different considerations. For example, the illustrative embodiments recognize and take into account that when light propagates through an optical waveguide, the light may have different wavelengths. The illustrative embodiments recognize and take into account that the light of the shortest wavelength, such as a pump light, can have a propagation mode such as a transverse electric (TE) 31 mode, which is a higher order mode. The illustrative embodiments recognize and take into account that the light of other wavelengths traveling through an optical waveguide can have a fundamental mode such as TE 11. The illustrative embodiments recognize and take into account that the light of the other wavelengths can be a signal light or an idler light generated within the optical waveguide as a result of the pump light traveling through the optical waveguide.

The illustrative embodiments recognize and take into account that the configuration of a nonlinear optical waveguide can affect the efficiency of generating at least one of a signal light or an idler light. As used herein, the phrase "at least one of," when used with a list of items, means different combinations of one or more of the listed items can be used, and only one of each item in the list may be needed. In other words, "at least one of" means any combination of items and number of items may be used from the list, but not all of the items in the list are required. The item can be a particular object, a thing, or a category.

For example, without limitation, "at least one of item A, item B, or item C" may include item A, item A and

item B, or item B. This example also may include item A, item B, and item C or item B and item C. Of course, any combinations of these items can be present. In some illustrative examples, "at least one of" can be, for example, without limitation, two of item A; one of item B; and ten of item C; four of item B and seven of item C; or other suitable combinations.

The illustrative embodiments recognize and take into account that it is desirable to avoid light of a particular wavelength having a first sign and a second sign that are opposite of each other. The illustrative embodiments recognize and take into account that the sign is for the amplitude of an electric field component of the light. The illustrative embodiments recognize and take into account that this condition can result in the nonlinear optical interaction of the light of one or more wavelengths being canceled or partially canceled.

Thus, the illustrative embodiments provide a method, apparatus, and system for moving light in optical waveguides with a desired level of light generation. In one illustrative example, an optical waveguide structure comprises a nonlinear optical waveguide with a central region, a first side region, and a second side region located within the nonlinear optical waveguide. The central region comprises a nonlinear optical material. The first side region is located on a first side of the central region. The second side region is located on a second side of the central region. The central region has a first nonlinear coefficient that is larger than a second nonlinear coefficient of the first side region and the second side region.

With reference now to the figures and, in particular, with reference to **Figure 1**, an illustration of a block diagram of an optical waveguide structure is

depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **100** comprises nonlinear optical waveguide **102** that comprises nonlinear optical material **104**.

In this illustrative example, a number of nonlinear optical processes **106** can occur within nonlinear optical waveguide **102**. As used herein, a "number of," when used with reference, to items means one or more items. For example, a "number of nonlinear optical processes **106**" is one or more of nonlinear optical processes **106**. Different nonlinear optical processes in nonlinear optical processes **106** can occur in different locations or regions within nonlinear optical waveguide **102**.

The nonlinear optical processes **106** can be three-wave mixing and four-wave mixing processes that generate light. For example, nonlinear optical process **106** can include at least one of spontaneous parametric down conversion (SPDC) and spontaneous four-wave mixing (SFWM). These nonlinear optical processes can generate light. Nonlinear optical process **106** also can include second harmonic generation, third harmonic generation, sum frequency generation and difference frequency generation. For example, pump light **108** can be input into nonlinear optical waveguide **102**. Nonlinear optical processes **106** can generate at least one of signal light **110** or idler light **112** in response to pump light **108** propagating through nonlinear optical material **104** in nonlinear optical waveguide **102**.

In this illustrative example, pump light **108**, signal light **110**, and idler light **112** are lights of different wavelengths. In this illustrative example, pump light **108** can have a wavelength that is shorter than the wavelength of signal light **110** and idler light **112**.

In this illustrative example, the structure of nonlinear optical waveguide **102** can be configured to increase light generation by nonlinear optical processes **106**. As depicted, nonlinear optical waveguide **102** comprises central region **114**, first side region **116**, and second side region **118**.

In this example, first side region **116** is on first side **120** of central region **114**. Second side region **118** is on second side **122** of central region **114**. In this illustrative example, first side **120** is opposite of second side **122**. In other words, first side region **116** and second side region **118** are on opposite sides of central region **114**.

As depicted, central region **114** comprises nonlinear optical material **104**. For example, central region 114 can be comprised of at least one of lithium niobate ($LiNbO_3$), silicon carbide, aluminum nitride, gallium nitride, gallium aluminum nitride, gallium phosphide, gallium aluminum phosphide, aluminum phosphide, gallium arsenide, gallium aluminum arsenide, aluminum arsenide, or some other suitable material.

First side region **116**, and second side region **118** comprise second material **119**. In this illustrative example, first side region **116** and second side region **118** can be comprised of second material **119** whose second-order nonlinear coefficient is smaller as compared to the second-order nonlinear coefficient of the nonlinear optical material **104** in central region **114** such that the nonlinear optical process is weaker and generates less light or does not generate light. In other words, nonlinear optical process in first side region **116** and second side region **118** does not generates less light or no light because the nonlinear optical process is weaker. For example, second material **119** in first side region **116**

and second side region **118** can be selected from at least one of silicon nitride, titanium dioxide silicon, silicon oxynitride, hafnia, or other suitable materials.

Nonlinear optical material **104** in central region **114** and second material **119** in first side region **116** and second side region **118** can generate light through other processes, such as direct emission of light.

In this example, nonlinear optical material **104** comprising the central region has first nonlinear coefficient **124** that is larger than second nonlinear coefficient **126** of second material **119** comprising first side region **116** and the second side region **118**. In this illustrative example, second nonlinear coefficient **126** can be selected such that a nonlinear optical interaction is reduced to about zero in first side region **116** and second side region **118**. In other words, second nonlinear coefficient **126** can be selected such that first side region **116** and second side region **118** have a reduced contribution to light generation **128**.

For example, nonlinear optical material **104** can be a first nonlinear optical material that has first nonlinear coefficient **124** in the form of a first second-order nonlinear coefficient with a magnitude that is at least one picometer/volt. First side region **116** and second side region **118** can be a second nonlinear optical material that has second nonlinear coefficient **126** in the form of a second second-order nonlinear coefficient whose magnitude is equal to or less than one third the magnitude of the first second-order nonlinear coefficient for the first nonlinear optical material.

In this illustrative example, this configuration of regions extends through some or all of nonlinear optical waveguide **102**. This configuration of central region **114**, first side region **116**, and second side region **118** can

provide a desired level of light generation **128** within nonlinear optical waveguide **102**.

As depicted, central region **114** has a set of dimensions **130** selected to increase light generation **128** in optical waveguide structure **100**. In this example, light generation **128** is increased in nonlinear optical waveguide **102** in optical waveguide structure **100**. In one illustrative example, the set of dimensions **130** can be selected from at least one of width **132**, height **134**, sidewall slope **135**, or some other dimension.

For example, width **132** can be for central region **114**. As another illustrative example, width **132** can be for first side region **116**, central region **114**, and second side region **118**. As yet another illustrative example, height **134** can be for central region **114**. In still another illustrative example, height **134** can be for first side region **116**, central region **114**, and second side region **118**. In another illustrative example, at least one of first side **120** or second side **122** for central region **114** can have a sidewall slope **135**, which can be defined as an angle.

As depicted, the set of dimensions **130** can be for the cross-section geometry **131** of nonlinear optical waveguide **102**. Cross-sectional geometry **131** includes a set of dimensions **130** that describe a set of cross-sections **133** in nonlinear optical waveguide **102**.

As used herein, a "set of," when used with reference to items, means one or more items. For example, a "set of dimensions **130**" is one or more of dimensions **130**.

The set of dimensions **130** can be selected such that light generation **128** increases for at least one of a signal light **110** or idler light **112** when pump light **108** travels through nonlinear optical waveguide **102**. For example, in the set of dimensions **130**, width **132** can be

selected to increase an overlap of an electromagnetic field for a light of interest with the central region such that light generation **128** is increased in nonlinear optical waveguide **102**. The light of interest can be pump light **108**, signal light **110** or idler light **112**.

For example, width **132** can selected to increase an overlap of the electromagnetic field that has a first sign for the light of interest within central region **114** and the electromagnetic field has a second sign for the light of interest in first side region **116** and second side region **118** such that light generation **128** is increased within nonlinear optical waveguide **102**. The light of interest can be at least one of pump light **108**, signal light **110**, or idler light **112**.

In this illustrative example, electric field amplitude of a first light traveling in nonlinear optical waveguide **102** has first sign **136** in nonlinear optical waveguide **102** in central region **114** while having second sign **138** in first side region **116** and second side region **118**. In other words, the sign is of the electric field amplitude of the light traveling through the different regions in nonlinear optical waveguide **102**.

In this illustrative example, the first light is the light that has the shortest wavelength of the lights of different wavelengths traveling through nonlinear optical waveguide **102**. For spontaneous parametric down conversion (SPDC), the first light is pump light **108**. For second harmonic generation, the first light can be the generated light such as signal light **110** and idler light **112**, which are both the second harmonic light. For spontaneous four-wave mixing (SFWM), the first light can be signal light **110**.

When first sign **136** is positive, second sign **138** is negative. When first sign **136** is negative, second sign

138 is positive. In this illustrative example, these signs are for the amplitude of the electric field. Nonlinear optical waveguide can be designed to reduce or avoid the amplitude of electric field of first light having both the first sign and the second sign in central region **114**.

In the illustrative example, the sign of the electric field component of first light in the central region **114** versus the sign the electric field component of first light in the side regions, first side region **116** and second side region **118**, affect light generation **128**. In other words, these two signs are opposite signs to each other.

By reducing second nonlinear coefficient **126** in first side region **116** and second side region **118**, the contribution to a nonlinear optical process from these side regions do not detract from the contribution to a nonlinear optical process from central region **114**. As a result, increased efficiency in light generation can occur using nonlinear optical waveguide **102** with central region **114**, first side region **116**, and second side region **118**.

The illustration of optical waveguide structure **100** in **Figure 1** is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be unnecessary. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.

For example, optical waveguide structure **100** include other components such as an optical coupler that couples nonlinear optical waveguide **102** to other optical waveguides. In another illustrative example, other structures can be present in nonlinear optical waveguide **102** in addition to central region **114**, first side region **116**, and second side region **118**. For example, a substrate in nonlinear optical waveguide **102** can be present on which these structures are formed.

Detailed embodiments of the claimed structures and methods are disclosed herein; however, it is to be understood that the disclosed embodiments are merely illustrative of the claimed structures and methods that may be embodied in various forms. In addition, each of the examples given in connection with the various embodiments is intended to be illustrative, and not restrictive.

Further, the figures are not necessarily to scale, some features may be exaggerated to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the methods and structures of the present disclosure.

For purposes of the description hereinafter, the terms "upper," "lower," "right," "left," "vertical," "horizontal," "top," "bottom," and derivatives thereof shall relate to the embodiments of the disclosure, as it is oriented in the drawing figures. The terms "positioned on" means that a first element, such as a first structure, is present on a second element, such as a second structure, wherein intervening elements, such as an interface structure, such as an interface layer, may

be present between the first element and the second element.

In this disclosure, when an element, such as a layer, region, or substrate is referred to as being "on" or "over" another element, the element can be directly on the other element or intervening elements can also be present. In contrast, when an element is referred to as being "directly on", "directly over", or "on and in direct contact with" another element, intervening elements are not present, and the element is in contact with the other element.

The processes, steps, and structures described below do not form a complete process flow for manufacturing integrated circuits. The disclosure can be practiced in conjunction with integrated circuit fabrication techniques currently used in the art, and only so much of the commonly practiced process steps are included as necessary for an understanding of the different examples of the present disclosure. The figures represent cross sections of a portion of an integrated circuit during fabrication and are not drawn to scale, but instead are drawn so as to illustrate different illustrative features of the disclosure.

Turning next to **Figure 2**, an illustration of a block diagram of a configuration for an optical waveguide structure is depicted in accordance with an illustrative embodiment. In the illustrative examples, the same reference numeral may be used in more than one figure. This reuse of a reference numeral in different figures represents the same element in the different figures.

As depicted in this example, nonlinear optical waveguide **102** comprises core region **200** and cladding region **201**. In this example, cladding region **201** is comprised of a dielectric material and core region **200** is

located within cladding region **201**. The dielectric material can be selected to have a smaller refractive index relative to the refractive index of core region **200**. The dielectric material of cladding region **201** can be selected from at least one of a silicon dioxide, a polymer, air, or other suitable material.

As depicted, cladding region **201** can be comprised of lower cladding region **204**, and upper cladding region **202**. As depicted, core region **200** is located between lower cladding region **204** and upper cladding region **202**. In this depicted example, the terms "upper" and "lower" are used to indicate relative locations of components with respect to each other. In this example, "upper" and "lower" can be relative locations on a structure in a vertical position. In a cross-sectional configuration, "upper" and "lower" are relative vertical positions. Left side and right side are relative horizontal positions.

Core region **200** can comprise a single spatially-uniform material and have a single value of its refractive index for a given wavelength of light. In this example, core region **200** also can comprise a spatially non-uniform material that is better described by a "net refractive index" whose value can be determined by the spatially varied refractive index distribution of that material.

A number of different components can form core region **200**. In this illustrative example, central region **114**, first side region **116**, and second side region **118** are components that form core region **200**.

In this illustrative example, core region **200** has core region refractive index **206**, and upper cladding region **202** has upper cladding refractive index **208** that is lower than core region refractive index **206**. As

depicted, lower cladding region **404** has lower cladding refractive index **210** that is lower than core region refractive index **206**.

In another illustrative example, upper cladding region **202** has height **212** that can be selected to compensate for a variation of the phase walk-off in the nonlinear optical waveguide. In this illustrative example, upper cladding region **202** can have height **212** selected to compensate for a variation in a set of dimensions **214** in core region **200** which can be one cause in the variation of the phase walk-off in the nonlinear optical waveguide.

For example, height **212** for upper cladding region **202** can be adjusted during fabrication to compensate for a variation in the set of dimensions **214** for core region **200** from an as-designed value for the set of dimensions **214**. In this illustrative example, the set of dimensions **214** can be, for example, a width or a height of core region **200**, the width or the height of central region **114**, or the width or the height of first side region **116** or second side region **118**. As depicted, height **212** of upper cladding region **202** can be sufficiently small that adjustments of height **212** can affect the effective refractive indices of the nonlinear waveguide modes.

In this illustrative example, lower cladding region **204** can be located on substrate **216**. Substrate **216** can be comprised of various materials depending on the implementation. For example, substrate **216** can comprise a set of materials selected from at least one of lithium niobate, silicon carbide, sapphire, quartz, alumina, silicon, germanium, or other suitable types of materials. Substrate **216** can be located on a wafer that is processed using fabrication equipment for semiconductor processing.

The illustration of structures for nonlinear optical waveguide **102** is provided to illustrate one manner in which nonlinear optical waveguide **102**can be implemented. This illustration is not meant to limit the manner in which nonlinear optical waveguide **102** can be configured in other illustrative examples. For example, cladding region **201** may be a single component rather than having upper cladding region **202** and lower cladding region **204**. Additionally, core region **200** is shown as a component located between upper cladding region **202** and lower cladding region **204**. In other illustrative examples, core region **200** can be located within upper cladding region **202**, lower cladding region **204**, or both of these regions in cladding region **201**.

In the illustrative example, a set of phase shifters **240** can be present in optical waveguide structure **100** and used with nonlinear optical waveguide **102**. The set of phase shifters **240** can be, for example, a set of electrodes **242**. The set of electrodes **242** can be used to affect the manner in which light propagates through the nonlinear optical waveguide **102**. For example, the set of electrodes **242** can be used to change the phase of a light of a particular wavelength propagating through nonlinear optical waveguide **102** or other types of optical waveguides.

Although in this illustrative example, the set of phase shifters **240** has been described as a set of electrodes **242**, other types of phase shifters may be used in addition to or in place of the set of electrodes **242** in other illustrative examples. For example, the set of phase shifters **240** can be a set of elements that is selected from at least one of a thermal element, shape memory alloy element, piezo electric element, or some other element that can emit energy to change the phase of

a light of a particular wavelength propagating through nonlinear optical waveguide **102**. The elements can also have different shapes and configurations selected to provide a desired change the phase of a light of a particular wavelength propagating through nonlinear optical waveguide **102** or other types of optical waveguides.

The set of electrodes **242** or other elements can apply a set of activations **244** that can take a number of different forms. For example, the set of activations can be selected from at least one of a voltage, a current, a thermal energy, an electrically induced strain, or some other type of energy that can be applied to an optical waveguide to affect the manner in which light propagates through nonlinear optical waveguide **102**. In particular, the energy can be used to affect the phase of a light of the particular wavelength propagating through nonlinear optical waveguide **102**.

Further, core region **200** can be first core region **249**, and second core region **250** can be present within optical waveguide structure **100**. In this illustrative example, second core region **250** can have different configurations.

For example, second core region **250** can have the same configuration as core region **200**. In another example, second core region **250** may only have a central region that may be a nonlinear optical material or may not be a nonlinear optical material.

With reference now to **Figure 3**, an illustration of a cross-sectional view of a nonlinear optical waveguide in an optical waveguide structure is depicted in accordance with an illustrative embodiment. Nonlinear optical waveguide **300** is an example of an implementation for

nonlinear optical waveguide **102** shown in block form in **Figure 1** and in **Figure 2**.

In this illustrative example, nonlinear optical waveguide **300** has core region **302**. In this illustrative example, core region **302** comprises a nonlinear optical material, such as x-cut lithium niobate ($LiNbO_3$). As depicted, nonlinear optical waveguide **300** also has cladding regions.

Nonlinear optical waveguide **300** has lower cladding region **306** and upper cladding region **308**. In this depicted example, the cladding regions can comprise at least one of silicon dioxide, air, or other suitable materials.

In this example, lower cladding region **306** is comprised of silicon oxide (SiO_2). As depicted, a first portion of upper cladding region **308** is comprised of silicon dioxide **303** and a second portion of upper cladding region **308** is comprised of air **305**. As depicted, silicon oxide in upper cladding region **308** has upper cladding region height **307**.

Although upper cladding region **308** is depicted as being silicon dioxide **303** and air **305**, upper cladding region **308** can take other forms in other illustrative examples. For example, upper cladding region **308** can be comprised of just silicon dioxide or air instead of an air and silicon dioxide combination.

Further, as depicted in this cross-sectional view, nonlinear optical waveguide **300** has side regions on either side of central region **304** that form core region **302**. As depicted, these two side regions are located laterally adjacent to central region **304**. In this illustrative example, the side regions comprise first side region **310** and second side region **312**, which are comprised of silicon nitride (Si_3N_4).

As depicted, nonlinear optical waveguide **300** has strip width **314**. In this cross-sectional view of nonlinear optical waveguide **300**, the cross-section of central region **304**, first side region **310**, and second side region **312** has strip width **314** that is selected to cause a phase matching condition.

Additionally, central region **304** in nonlinear optical waveguide **300** has center region top width **316**. As depicted, center region top width **316** can be selected to increase an overlap of an electromagnetic field for a light of interest with central region **304** such that light generation is increased in nonlinear optical waveguide **300**. As another illustrative example, sidewall **320** and sidewall **322** for central region **304** can have a side slope defined by angle **326** and angle **328**.

In this illustrative example, silicon nitride can be a suitable material for first side region **310** and second side region **312** because silicon nitride has a minimal second-order optical nonlinearity and the refractive index of silicon nitride is slightly smaller than the refractive index of lithium niobate, the nonlinear optical material used in central region **304**. In this depicted example, the refractive index of silicon nitride can be less than 10% smaller than the refractive index of lithium niobate.

As depicted, nonlinear optical waveguide **300** can be especially suitable for modal phase matching in which the shortest wavelength of the light involved in the nonlinear optical process is in the $TE_{xy} = TE_{31}$ mode (or in the $TM_{xy} = TM_{31}$ mode). For this nomenclature, the x-axis of the cross-section is in the horizontal direction and the y-axis of the cross-section is in the vertical direction. These axes are reference directions in a cross-sectional depiction and are not necessarily the

same as the X, Y, and Z axes of a lithium niobate crystal. For a spontaneous parametric down conversion nonlinear optical process, a pump light has the shortest wavelength (highest energy) and is in the TE_{31} mode.

The illustration of nonlinear optical waveguide **300** is provided as an example of one implementation for nonlinear optical waveguide **102** shown in block form in **Figure 1** and **Figure 2**. This illustration is not meant to limit the manner in which nonlinear optical waveguide **300** can be implemented in other illustrative examples. For example, a layer of a material comprising first side region **310**, second side region **312**, or some other material can be located over at least one of central region **304**, first side region **310**, or second side region **312**.

With reference now to **Figure 4**, an illustration of field profiles in a nonlinear optical waveguide is depicted in accordance with an illustrative embodiment. As depicted, field profiles **400** are for light in a nonlinear optical waveguide, such as nonlinear optical waveguide **300** in **Figure 3**. In this illustrative example, the pump light is in the TE_{31} mode and the signal light and the idler light are in the TE_{11} (or fundamental) mode.

As depicted in field profile **402**, the TE_{31} pump mode in a cross-section of nonlinear optical waveguide **102** has 3 lobes, center lobe **404**, side lobe **406**, and side lobe **408**. The magnitude of the electric field amplitude is largest near the central portions of these lobes as seen in field profile **402**. For a higher-order mode of the waveguided light, such as the TE_{31} pump mode, the amplitude of the electric field can have a positive value or a negative value, as seen in field profile **402**.

Also, the electric field amplitude distribution can have a large magnitude (having a value close to +1 or -1)

or can have a small magnitude (having a value close to 0). The portions of the electric field amplitude distribution having a large magnitude can be called the lobes of the electric field distribution.

As depicted, field profile **402** is for an optical field within core region **302**, which is formed by central region **304**, first side region **310**, and second side region **312 in Figure 3**. In this illustrative example, central region **304** is shown by outline **401**, first side region **310** is shown by outline **403**, and second side region **312** is shown by outline **405**.

In this depicted example profile, the center lobe **404** overlaps the nonlinear optical material in central region **304** in nonlinear optical waveguide **300** in which central region **304** is shown by outline **401**. Side lobe **406** overlaps first side region **310** as shown by outline **403** for first side region **310**. As depicted, lobe **416** overlaps second side region **312** as shown by outline **405** for second side region **312**.

In this illustrative example, center lobe **404** has an amplitude with a sign that is positive. In contrast, side lobe **406** and side lobe **408**, have amplitudes of the opposite sign, in which the signs are negative.

Electric field profile **410** for the signal light has lobe **412**, and electric field profile **414** for the idler light has lobe **416**. The electric field profiles or spatial distributions illustrate the waveguide modes for the signal and idler light in a given cross-section for nonlinear optical waveguide **300**. Field profile **410** and field profile **414** each have one peak, or lobe, for the electric field amplitudes. As depicted in field profile **410** and field profile **414**, peak amplitudes of signal and idler electric fields have a positive sign.

As depicted, field profile **410** is shown for a signal light optical field within core region **302** as shown by outline **420**. In this illustrative example, field profile **414** is shown for a signal light optical field within core region **302** as shown by outline **422**.

For purposes of illustration, the entire waveguide cross-section can be assumed to be comprised of a nonlinear optical material. For example, first side region **310**, second side region **312**, and central region **304** can all comprised of a nonlinear optical material. For example, nonlinear optical material can have $d_{NL} < 0$, i.e. d_{NL} is a negative value.

In the illustrative example, equation (2) below can be considered for the spatial combination of the three electric field peaks in the pump mode shown in field profile **402**. These three electric field peaks are center lobe **404**, side lobe **406**, and side lobe **408** in field profile **402** for the pump light. The rate of generation of signal light contributed by the center lobe is positive using equation (2) below. Because the signal and idler modes have electric fields amplitude that peak in the center of nonlinear optical waveguide in this example, the central region will have the greatest contribution to the rate of signal generation.

Considering now the contributions to equation (2) below from the two side peaks of the pump mode, the rate of generation of signal light is negative in this example. The electric field amplitude of the pump mode has one sign in center lobe **404**, and opposite signs on side lobe **406** and side lobe **408**. In this illustrative example, the amplitude of the idler field has the same sign across all of nonlinear optical waveguide **300**. As a result, the contribution to the generation of a signal light and an idler light has one sign in the center of

nonlinear optical waveguide **300** in central region **304**, and an opposite sign for the sides of nonlinear optical waveguide **300** in first side region **310** and second side region **312**.

Because the electric field amplitude of the pump mode has one sign in the center lobe, and opposite signs in the side lobes, but the amplitude of the lobe(s) of the electric field amplitude of the idler mode has the same sign across the entire structure, the contribution to the rate of generation of signal light will have one sign for the center of the structure, and the opposite sign for the sides of the structure. In the illustrative example, difference in the sign of the electric field amplitude in different regions of the nonlinear optical waveguide **300** results in the difference in the sign of the contribution those regions make to the rate of generation of signal light.

Thus, the light generation contributed by the side regions, first side region **310** and second side region **312**, versus central region **304** is a competitive process. Because the amplitudes of idler electric fields (and also of signal electric fields for the case of spontaneous parametric down conversion (SPDC)) are relatively weak in first side region **310** and second side region **312**, the magnitude of the contribution to light generation by these side regions is smaller than the magnitude of the contribution to light generation by central region **304**.

Next, when first side region **310** and second side region **312** are comprised of a material that has little-to-no nonlinearity in the depicted examples the rate of light generation of a signal light and an idler light contributed by the side regions is effectively zero, according to equation (2) below. In this illustrative example, $d_{effNL} \approx 0 d_{effNL} \approx 0$ in the two side regions.

Thus, the rate of light generation of the signal light (and also of the idler light in the case of spontaneous parametric down conversion (SPDC)) in nonlinear optical waveguide **300** can be dominated by the rate of light generation of the signal light (and also of idler light in the case of spontaneous parametric down conversion (SPDC)) in central region **304** of nonlinear optical waveguide **300**. In this example, center lobe **404** of the pump light mode in field profile **402** most strongly overlaps with the idler modes in field profile **414** (and for the case of spontaneous parametric down conversion (SPDC), also with the signal modes in field profile **410**).

In this illustrative example, the side lobes in field profile **402** for the pump mode do not detract from the rate of light generation of signal light, and idler light, or both in nonlinear optical waveguide **300** because these side lobes, side lobe **406** and side lobe **408**, do not significantly overlap a material with a large nonlinear coefficient. Thus, the competition between contributions from different spatial regions to the nonlinear optical process can be significantly reduced, if not entirely eliminated.

In this example, using all 3 lobes of the pump mode shown in field profile **402** for the nonlinear process results in a cancellation of the contributions from different spatial regions to nonlinear optical processes. This cancellation can occur because of the differing signs of electric field amplitude in the differing pump mode lobes such as side lobe **406** and side lobe **408** versus center lobe **404**.

With nonlinear optical waveguide **300**, the side lobes of the pump mode in field profile **402** are located in a material that has low nonlinearity relative to the nonlinearity of central region **304**. As a result, the

contribution of central region **304** in nonlinear optical waveguide **300** with high nonlinearity level is not cancelled by the contribution from the side lobes of the pump mode in field profile **402**, which would otherwise subtract from the contribution of central region **304** to the nonlinear optical process. The first nonlinear optical coefficient in central region **304** and second nonlinear optical coefficient in first side region **310** and second side region **312** can be selected to have relative values to provide a desired level of light generation or light generation rate in nonlinear optical waveguide **300**.

Turning next to **Figure 5**, an illustration of field profiles in central region of a nonlinear optical waveguide is depicted in accordance with an illustrative embodiment. As depicted, field profiles **500** are for a central region such as central region **304** in nonlinear optical waveguide **300** in **Figure 3**.

As depicted, field profile **502** is for a pump light optical field, field profile **504** is for a signal light optical field, field profile **506** is for an idler light optical field. In the illustrative example, these field profiles are for central region **304** as indicated outline **508** in field profiles **500**. The fields illustrative within outline **508** in the different field profiles are the portions of the optical fields that are involved in a nonlinear optical process that generates light in nonlinear optical waveguide **300**.

In nonlinear optical waveguide **300** in **Figure 3**, the rate of generation of signal light from pump light and idler light in an exemplary second-order nonlinear optical process of difference frequency generation can be described by the coupled-wave equation, given below for signal light:

$$\frac{dA_s}{dz} = d_{eff} A_p A_i^* \frac{i2\pi}{n_s \lambda_s} e^{i\Delta kz} \quad (1)$$

where A_s is the electric field amplitude of signal light **110**, A_p is the electric field amplitude of pump light **108**, A_i^* is the complex conjugate of electric field amplitude of idler light **112**, d_{eff} is the effective nonlinear optical coefficient, λ_s is the vacuum wavelength of the signal light, n_s is the effective refractive index of the signal light propagating in nonlinear optical waveguide **300**, Δk is the wavevector mismatch, **z** is the distance propagated by the optical fields, and i is imaginary unit ($i^2 = -1$).

In this example, n_s is the effective refractive index for the signal light. The "effective" nonlinear optical coefficient d_{eff} is described by the values for first nonlinear coefficient in central region **304** and second nonlinear coefficient in first side region **310** and second side region **312**, as well as by the spatial distributions of the optical fields. In the illustrative example, "optical field" is the propagating electro-magnetic field of the light.

In the depicted example, the dimensions describing the cross-section geometry for nonlinear optical waveguide **300** can be selected to meet a particular phase-matching condition, or value for $\Delta k = 2\pi(\frac{n_p}{\lambda_p} - \frac{n_i}{\lambda_i} - \frac{n_s}{\lambda_s})$, which depends on the particular implementation. The first three factors as well as the wave-vector mismatch in the exponential on the right-hand-side of equation (1) are terms of interest in light generation for nonlinear optical waveguide **300**. For any point along the longitudinal dimension z of the waveguide, the generation

of the signal light will depend on the transverse or spatial variation of the nonlinear optical coefficient in the waveguide's cross-sectional structure and on the spatial variation of the electric fields for the pump light and the idler light. These spatial variations are described in the spatially integrated value for d_{eff},

$$\frac{dA_s}{dz} \propto d_{eff} = \iint d_{NL} u_p u_i dx dy \quad (2)$$

In equation (2), d_{NL} is the nonlinear optical coefficient of the material, and can have a different value different for different spatial regions of the waveguide; u_p is the normalized electric field distribution for the pump light and u_i is the normalized electric field distribution for the idler light. The integration can be performed over the transverse or cross-sectional dimensions.

The electric field distributions shown in **Figure 5** are only those portions for which the waveguide material has a value for d_{NL} that is non zero. Only these portions of the electric field distributions contribute to the result of the integration done to obtain the value for d_{eff} as describe by equation (2).

Turning now to **Figure 6**, an illustration of a graph of an optical field overlap factor for different configurations of nonlinear optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, graph **600** illustrates an optical field overlap factor as a function of strip width. In this illustrative example, graph **600**, represents optical field overlap factors generated after performing the integration in equation (2) with a normalized value of 0 or 1 for the material nonlinear optical coefficient d_{NL}. The normalized value is one when the optical field is within outline **401** or outline **508**

and is 0 when the optical field is outside of this outline **401** or outline **508** as depicted in **Figure 4** and **Figure 5**.

In this example, y-axis **602** represents the optical field overlap factor, and x-axis **604** represents strip width in micrometers. The lines in graph **600** illustrate values of the optical field overlap factor obtained for various configurations of nonlinear optical waveguides.

The lines in section **606** are obtained using a material with a low value or normalized to 0 for material nonlinear optical coefficient d_{NL}.

As depicted, the lines in section **606** depict optical field overlap factors for nonlinear optical waveguides that have a spatially uniform lithium niobate core region, whose normalized nonlinear optical coefficient has a value of 1. In section **606**, line **652** is for a waveguide with a spatially uniform lithium niobate core region and an upper cladding height of 0.50 μm, and line **654** is for a waveguide with a spatially uniform lithium niobate core region and an upper cladding height of 0.45 μm. In this example, the lines in section **606** result from a nonlinear optical waveguide whose core region comprises spatially uniform lithium niobate and does not have any side regions.

In this illustrative example, the lines in section **608** illustrate optical field overlap factors for nonlinear optical waveguides whose core region comprises a central region and two side regions. The lines in section **608** are obtained when the central region has a normalized nonlinear optical coefficient d_{NL} equal to 1 and the two side regions have a normalized nonlinear optical coefficient d_{NL} equal to 0.

Examples of these types of waveguides include nonlinear optical waveguide **102** in **Figure 1**, nonlinear

optical waveguide **300** in **Figure 3**, nonlinear optical waveguide **702** in **Figure 7**, nonlinear optical waveguide **902** in **Figure 9**, and nonlinear optical waveguide **1002** in **Figure 10**. These nonlinear optical waveguides can have a lithium niobate center region and silicon nitride side regions.

In section **608**, line **656** is for a nonlinear optical waveguide with a center region width of 0.3 μm and an upper cladding height of 0.46 μm; and line **658** is for a nonlinear optical waveguide with a lithium niobate center region and silicon nitride side regions having a center region width of 0.3 μm and an upper cladding height of 0.47 μm.

In the illustrative examples, the generation of light in the nonlinear optical waveguides depends on the square of the optical field overlap factor. As a result, increasing the optical field overlap factor results in an increase in the generation of light such as at least one of a signal light or an idler light from a pump light propagating through the nonlinear optical waveguide.

The selection of values for the center width for a central region with side regions as depicted in the illustrative examples can result in an optical field overlap factor that provides greater performance in light generation as compared to current nonlinear optical waveguides as can be seen by the difference in the optical field overlap factor in section **608** and section **606**.

Turning now to **Figure 7**, an illustration of a cross-sectional view of an optical waveguide structure with electrodes is depicted in accordance with an illustrative embodiment. Optical waveguide structure **700** is an example of an implementation for optical waveguide structure **100** in **Figure 1** and **Figure 2**.

In this illustrative example, optical waveguide structure **700** comprises nonlinear optical waveguide **702**, electrode **722**, and electrode **724**. Nonlinear optical waveguide **702** is an example of an implementation for nonlinear optical waveguide **102** shown in block form in **Figure 1** and in **Figure 2**.

In this illustrative example, nonlinear optical waveguide **702** comprises core region **704**, upper cladding region **706**, and lower cladding region **708**. Lower cladding region **708** is formed on a silicon substrate **710**. As depicted, upper cladding region **706** and lower cladding region **708** are formed using an oxide (SiO_2).

As depicted, core region **704** comprises central region **712**, first side region **714**, and second side region **716**. In this illustrative example, central region **712** is comprised of lithium niobate ($LiNbO_3$). First side region **714** and second side region **716** are comprised of silicon nitride (Si_3N_4).

As depicted, core region **704** has strip width **718**, and central region **712** has center width **720**. Core region **704** also has strip height **719**.

These dimensions can be selected to obtain desired propagation of light through nonlinear optical waveguide **702**. For example, at least one of strip width **718** or strip height **719** can be selected to obtain a desired phase matching condition or a desired value for the wave-vector mismatch Δk. Center width **720** can be selected to increase an overlap of a first portion of an electromagnetic field having a first sign for a light of interest within central region **712** and such that a second portion of an electromagnetic field having the second sign is located in first side region **714**, and second side region **716** such that light generation is increased in nonlinear optical waveguide **702**.

In this illustrative example, optical waveguide structure **700** also includes electrode **722** and electrode **724**. As depicted, electrode **722** and electrode **724** form an optical waveguide structure that can function as an optical phase shifter that can shift the phases of the electromagnetic fields of light traveling through nonlinear optical waveguide **702**. The fields can be, for example, transverse electric (TE) fields or transverse magnetic (TM) fields. In other illustrative examples, a single electrode can be located in proximity to the waveguide core region. In yet other illustrative examples, a third electrode can be placed over core region **704** and upper cladding region **706**. In yet another illustrative example, electrode **722** or electrode **724** can be fabricated to extend over core region **704**.

Turning now to **Figure 8**, an illustration of a cross-sectional view of an optical waveguide structure is depicted in accordance with an illustrative embodiment. Optical waveguide structure **800** is an example of an implementation for optical waveguide structure **100** in **Figure 1**.

In this illustrative example, optical waveguide structure **800** comprises nonlinear optical waveguide **802**, electrode **822**, electrode **824**, and electrode **825**. Nonlinear optical waveguide **802** is an example of an implementation for nonlinear optical waveguide **102** shown in block form in **Figure 1** and in **Figure 2**.

In this illustrative example, nonlinear optical waveguide **802** comprises core region **804**, upper cladding region **806**, and lower cladding region **808**. Lower cladding region **808** is formed on silicon substrate **810**. As depicted, upper cladding region **806** and lower cladding region **808** are formed using an oxide (SiO_2).

As depicted, core region **804** comprises central region **812**, first side region **814**, and second side region **816**. In this illustrative example, central region **812** is comprised of lithium niobate ($LiNbO_3$). First side region **814** and second side region **816** are comprised of silicon nitride (Si_3N_4).

As depicted, core region **804** has strip width **818** and strip height **819**. In this example, central region **812** has center width **820**. These two dimensions can be selected to obtain desired propagation of light through nonlinear optical waveguide **702**. For example, at least one of strip width **818** or strip height **819** can be selected to obtain a desired phase matching condition. Center width **820** can be selected to increase an overlap of an electromagnetic field having a first sign for a light of interest within central region **812** while the electromagnetic signal has a second side in first side region **814** and second side region **816** such that light generation is increased in nonlinear optical waveguide **702**.

In this illustrative example, optical waveguide structure **800** also includes electrode **822** and electrode **824**. As depicted, electrode **822**, electrode **724**, and electrode **825** enable optical waveguide structure **800** to function as a phase shifter that can shift phases of the electromagnetic fields in light traveling through nonlinear optical waveguide **802**. The fields can be, for example, transverse electric (TE) fields or transverse magnetic (TM) fields. In other illustrative examples, a single electrode can be used.

In **Figure 9**, another illustration of a cross-sectional view of an optical waveguide structure with two core regions is depicted in accordance with an illustrative embodiment. Optical waveguide structure **900**

is an example of an implementation for optical waveguide structure **100** in **Figure 1** and **Figure 2**. Optical waveguide structure **900** can function as optical coupler and can be a wavelength selective coupler.

In this illustrative example, optical waveguide structure **900** comprises nonlinear optical waveguide **902** and nonlinear optical waveguide **904**. Nonlinear optical waveguide **902** and nonlinear optical waveguide **904** are an example of an implementation for nonlinear optical waveguide **102** shown in block form in **Figure 1** and in **Figure 2**.

As depicted, optical waveguide structure **900** comprises nonlinear optical waveguide **902** and nonlinear optical waveguide **904**. In this illustrative example, nonlinear optical waveguide **902** and nonlinear optical waveguide **904** have upper cladding region **908** and lower cladding region **910**. Lower cladding region **910** is formed on silicon substrate **912**. Upper cladding region **908** and lower cladding region **910** are comprised of an oxide (SiO_2).

In this illustrative example, nonlinear optical waveguide structure **900** has first core region **914** and second core region **926** that are separated from each other by gap **906**. This first core region **914** comprises central region **916**, first side region **918**, and second side region **920**. As depicted, central region **916** is comprised of lithium niobate ($LiNbO_3$). First side region **918** and second side region **920** are comprised of silicon nitride (Si_3N_4).

As depicted, first core region **914** has strip width **922**. Central region **916** has center width **924**. These two dimensions can be selected to obtain desired propagation of light through nonlinear optical waveguide **902** and the

coupling of light between first core region **914** and second core region **926**.

As depicted, nonlinear optical waveguide **904** has second core region **926**. In this example, second core region **926** comprises central region **928** and does not include side regions as compared to first core region **914** in nonlinear optical waveguide **902**. Central region **928** is comprised of lithium niobate ($LiNbO_3$) in this depicted example.

Central region **928** has strip width **930**. This width can be selected to adjust optical properties in the propagation of light through optical waveguide structure **900** and the coupling of light between the two core regions **914** and **926**.

As depicted, first core region **914** has strip height **932** and second core region **926** has strip height **934**. These heights can also be adjusted to obtain desired optical transmission properties. Adjusting the strip height and the strip width can change the effective refractive index for the pump light (n_p), signal light (n_s), and idler light (n_i). These changes can affect the coupling of light between the core regions. These changes can also affect the phase shift contributed by the optical coupler to the phase match. For separate waveguides, these changes also affect the wave-vector mismatch and the phase matching, which in turn affects the efficiency of the nonlinear optical generation process.

Turning to **Figure 10**, yet another illustration of a cross-sectional view of an optical waveguide structure with two core regions is depicted in accordance with an illustrative embodiment. Optical waveguide structure **1000** is an example of an implementation for optical waveguide structure **100** in **Figure 1** and **Figure 2**.

Optical waveguide structure **1000** can function as an optical coupler.

In this illustrative example, optical waveguide structure **1000** comprises nonlinear optical waveguide **1002** and optical waveguide **1004**. Nonlinear optical waveguide **1002** is an example of an implementation for nonlinear optical waveguide **102** shown in block form in **Figure 1** and in **Figure 2**. Optical waveguide structure **1000** is similar to optical waveguide structure **900** in **Figure 9** except that optical waveguide **1004** is present in place of nonlinear optical waveguide **904** in **Figure 9**.

In this illustrative example, nonlinear optical waveguide **1002** and optical waveguide **1004** have upper cladding region **1008** and lower cladding region **1010**. Lower cladding region **1010** is formed on silicon substrate **1012**. Upper cladding region **1008** and lower cladding region **1010** are comprised of an oxide (SiO_2).

As depicted, optical waveguide structure **1000** comprises first core region **1014** and second core region **1026** that are separated from each other by gap **1006**. In this illustrative example, nonlinear optical waveguide **1002** has first core region **1014**. This first core region comprises central region **1016**, first side region **1018**, and second side region **1020**. As depicted, central region **1016** is comprised of lithium niobate ($LiNbO_3$). First side region **1018** and second side region **1020** are comprised of comprised of silicon nitride (Si_3N_4).

As depicted, first core region **1014** has strip width **1022**. Central region **1016** has center width **1024**. These two dimensions can be selected to obtain desired propagation of light through nonlinear optical waveguide **1002** and the coupling of light between first core region **1014** and second core region **1026**.

As depicted, optical waveguide **1004** has second core region **1026**. In this example, second core region **1026** comprises central region **1028**. In this particular example, central region **1028** is not comprised of nonlinear optical material. As depicted, central region **1028** is comprised of silicon nitride (Si_3N_4).

Central region **1028** has strip width **1030**. This width can be selected to adjust optical properties in the propagation of light through optical waveguide **1004** and the coupling of light between first core region **1014** and second core region **1026**.

As depicted, first core region **1014** has strip height **1032** and second core region **1026** has strip height **1034**. These heights can also be adjusted to obtain desired optical transmission properties.

With reference to **Figure 11**, another illustration of a cross-sectional view of an optical waveguide structure with merged core regions that form a multimode interference coupler is depicted in accordance with an illustrative embodiment. Optical waveguide structure **1100** is an example of optical waveguide device that can be used in optical waveguide structure **100** in **Figure 1** and **Figure 2**. Optical waveguide structure **1100** can function as an optical coupler.

In this illustrative example, optical waveguide structure **1100** comprises a multimode interference coupler core **1105** that can be used in optical waveguide structure **100** shown in block form in **Figure 1** and **Figure 2** to couple nonlinear optical waveguide **102** to another optical waveguide that can be used in optical waveguide structure **100**.

As depicted, nonlinear optical waveguide structure **1100** has upper cladding region **1108** and lower cladding region **1110**. Lower cladding region **1110** is formed on

silicon substrate **1112**. Upper cladding region **1108** and lower cladding region **1110** are comprised of an oxide (SiO_2).

In this illustrative example, multimode interference coupler in optical waveguide **1100** has first core region **1114** that is an example of core region **200** in **Figure 2**. This core region comprises central region **1116**, first side region **1118**, and second side region **1120**. As depicted, central region **1116** is comprised of lithium niobate ($LiNbO_3$). First side region **1118** and second side region **1120** are comprised of silicon nitride (Si_3N_4). As depicted, central region **1116** in first core region **1114** has center width **1124**.

As depicted, multimode interference coupler core **1105** in optical waveguide structure **1100** also has second core region **1126** with central region **1128**. In this example, central region **1128** in second core region **1126** has width **1130** and is comprised of lithium niobate ($LiNbO_3$) in this depicted example. This width can be selected to adjust optical properties in the propagation of light through optical waveguide structure **1100**.

As depicted, first core region **1114** and second core region **1128** has strip height **1134**. This height can also be adjusted to obtain desired optical transmission properties.

In **Figure 12**, yet another illustration of a cross-sectional view of an optical waveguide structure with merged core regions that form a multimode interference coupler is depicted in accordance with an illustrative embodiment. Optical waveguide structure **1200** is an example of an optical waveguide component that can be used in optical waveguide structure **100** in **Figure 1** and **Figure 2**. Optical waveguide structure **1200** can function as an optical coupler.

In this illustrative example, optical waveguide structure **1200** comprises nonlinear optical waveguide **1202** that is an example of an implementation for nonlinear optical waveguide **102** shown in block form in **Figure 1** and in **Figure 2**. Optical waveguide structure **1200** is similar to optical waveguide structure **1100** in **Figure 11**.

As depicted, nonlinear optical waveguide **1202** forms multimode interference coupler core **1205**.

In this illustrative example, has upper cladding region **1208** and lower cladding region **1210**. Lower cladding region **1210** is formed on silicon substrate **1212**. Upper cladding region **1208** and lower cladding region **1210** are comprised of an oxide (SiO_2).

In this illustrative example, nonlinear optical waveguide **1202** has first core region **1214** that is an example of core region **200** in **Figure 2**. This first core region comprises central region **1216**, first side region **1218**, and second side region **1220**. As depicted, central region **1216** is comprised of lithium niobate ($LiNbO_3$). First side region **1218** and second side region **1220** are comprised of comprised of silicon nitride (Si_3N_4).

As depicted, central region **1216** in first core region **1214** has center width **1224**. This width can be selected to obtain desired propagation of light through nonlinear optical waveguide **1202**.

As depicted, multimode interference coupler core **1205** has second core region **1226**. In this example, second core region **1226** is not comprised of nonlinear optical material. As depicted, second core region **1226** region **1228** is comprised of silicon nitride (Si_3N_4).

As depicted, first core region **1214** and second core region **1226** have strip height **1234**. This height can be adjusted to obtain desired optical transmission properties.

Turning now to **Figure 13**, an illustration of a cross-sectional view of an optical waveguide structure is depicted in accordance with an illustrative embodiment. Optical waveguide structure **1300** is an example of an implementation for optical waveguide structure **100** in **Figure 1** and **Figure 2**.

In this illustrative example, optical waveguide structure **1300** comprises nonlinear optical waveguide **1302**. Nonlinear optical waveguide **1302** is an example of an implementation for nonlinear optical waveguide **102** shown in block form in **Figure 1** and in **Figure 2**.

In this illustrative example, nonlinear optical waveguide **1302** comprises core region **1304**, upper cladding region **1306**, and lower cladding region **1308**. Lower cladding region **1308** is formed on a silicon substrate **1310**. As depicted, upper cladding region **1306** is a two-part cladding region comprises air **1305** and silicon oxide **1307**. As depicted, lower cladding region **1308** that is comprised of silicon oxide.

As depicted, core region **1304** comprises central region **1312**, first side region **1314**, second side region **1316**, and top region **1317**. In this illustrative example, central region **1312** is comprised of lithium niobate ($LiNbO_3$). First side region **1314**, second side region **1316**, and top region **1317** are comprised of silicon nitride (Si_3N_4).

As depicted, first side region **1314**, second side region **1316** are on either side of central region **1312**, and top region **1317** is located over central region **1312**. Although first side region **1314**, second side region **1316**, and top region **1317** are described as separate elements, these elements can be a single structure formed at the same time during fabrication of nonlinear optical waveguide **1302**.

In this illustrative example, top region **1317** affects the electric field distributions for the pump light, signal light, and idler light. This top region can also affect the values for the effective refractive indices n_p, n_s and n_i of the pump light, signal light, and idler light. Top region **1317**, when present in a phase shifter, can improve the efficiency of the phase shifter.

As depicted, core region **1304** has strip width **1318**, and central region **1312** has center width **1320**. These two dimensions can be selected to obtain a desired propagation of light through nonlinear optical waveguide **1302**.

As depicted, upper cladding **1306** has height **1319**. Height **1319** is measured based on the height of silicon oxide **1307** in upper cladding region **1306**.

The illustrations of the different cross-sections in **Figures 3** and **7-13** are provided as a non-limiting examples of implementations for optical waveguide structure **100** in **Figure 1** and **Figure 2**. These illustrations provide illustrative examples of how different cross-sections can be implemented and are not meant to be limiting as to how other illustrative examples can be included.

For example, in other implementations, the sides of central region **304**, first side region **310** and second side region **312** in core region **302** of nonlinear optical waveguide **300** in **Figure 3**, can have sides that110 are perpendicular to lower cladding region **306** instead of angled sides as depicted in **Figure 3**. Examples of perpendicular sides are shown in **Figures 7-13**. The angled sides are not meant to limit the other examples to particular angles. In yet similar illustrative examples, the central region can have perpendicular sides while the side regions have angled sides. In yet other depicted

examples, the central region can have a perpendicular side while the side regions have angled sides.

As yet another example, other types of tuning elements may be used in addition to or in place of tuning electrodes that apply a voltage in **Figure 7**. For example, a tuning element can cause phase shifting of optical signals traveling through an optical waveguide using an activation such as a thermal energy, a strain, or some other type of energy that can be applied to the optical waveguide to affect the manner in which light propagates through the optical waveguide.

With reference now to **Figure 14**, an illustration of an optical waveguide structure is depicted in accordance with an illustrative embodiment. As depicted, optical waveguide structure **1400** comprises main nonlinear optical waveguide **1402**, first extension optical waveguide **1404**, and second extension optical waveguide **1406**. In this illustrative example, main nonlinear optical waveguide **1402** and first extension optical waveguide **1404** are comprised of nonlinear material.

As depicted, first extension optical waveguide **1404** can be an idler loop extension optical waveguide, and second extension optical waveguide **1406** can be a pump loop extension waveguide. Additionally, area **1440** can be an ending first extension wavelength selective coupler located in an ending first extension location in main nonlinear optical waveguide **1402** and first extension optical waveguide **1404**.

In this illustrative example, light can propagate through these optical waveguides. For example, light comprising a pump light, a signal light, and an idler light can propagate through one or more of main nonlinear optical waveguide **1402**, first extension optical waveguide **1404**, and second extension optical waveguide **1406**. In

this illustrative example, optical waveguide structure **1400** incorporates one or more nonlinear optical processes that generate at least one of a signal light or an idler light using a pump light input into optical waveguide structure **1400** through pump input waveguide **1408**.

As depicted, optical waveguide structure **1400** also comprises signal output waveguide **1410** and idler output waveguide **1412**. In this illustrative example, pump input waveguide **1408** operates to input a pump light into second extension optical waveguide **1406** in optical waveguide structure **1400**. Signal output waveguide **1410** operates to output a signal light from main nonlinear optical waveguide **1402**. Idler output waveguide **1412** operates to output light from first extension optical waveguide **1404**.

Additionally, optical waveguide structure **1400** also includes electrode **1414**, electrode **1416**, and electrode **1418**. As depicted, electrode **1414** and electrode **1416** are adjacent to portions of main nonlinear optical waveguide **1402**. These electrodes can operate to shift the phases of one of optical signals propagating through main nonlinear optical waveguide **1402**. These optical signals can be, for example, selected from at least one of a pump light, a signal light, or an idler light.

In this illustrative example, electrode **1418** is located adjacent to a portion of first extension optical waveguide **1404**. This electrode operates to shift the phase of an idler light propagate through first extension optical waveguide **1404**.

Optical waveguide structure **1400** can be implemented using one or more of optical waveguide structures such as the optical waveguide structures depicted in cross-sectional form in **Figure 3** and **Figures 7-13**. For example, area **1420** containing main nonlinear optical waveguide **1402** and second extension optical waveguide

1406 can have a cross-sectional structure as shown for optical waveguide structure 1000 in Figure 10 or for optical waveguide structure 1200 in Figure 12. As another example, area 1422 contains main nonlinear optical waveguide 1402 and first extension optical waveguide 1404. This area can have a cross-sectional structure as shown for optical waveguide structure 900 in Figure 9 or for optical waveguide structure 1100 in Figure 11.

As depicted, area 1422 can be for a first extension wavelength selective coupler located at a first extension starting location in main nonlinear optical waveguide 1402 and the first extension optical waveguide 1404.

In this depicted example, area 1424 includes main nonlinear optical waveguide 1402 and electrode 1414. Additionally, area 1426 includes main nonlinear optical waveguide 1402 and electrode 1416. These two areas can have a cross-sectional structure as shown for optical waveguide structure 700 in Figure 7 in which a single tuning electrode is present. As yet another example, area 1428 includes main nonlinear optical waveguide 1402. Area 1428 can have a cross-sectional structure as shown for nonlinear optical waveguide 300 in Figure 3.

As depicted, area 1440 is an optical coupler for coupling a signal light from main nonlinear optical waveguide 1402 to signal output waveguide 1410. This area can have a cross-sectional structure as shown for optical waveguide structure 1000 in Figure 10.

In this example, light of different wavelengths can travel in different loops having different lengths within optical waveguide structure 1400. For example, first light of a first wavelength can travel within a first loop within main nonlinear optical waveguide 1402. The first light can be a signal light in this example. A

second light of the second wavelength can travel in a second loop within main nonlinear optical waveguide **1402** and first extension optical waveguide **1404** in which the second loop has a second length for the second light of the second wavelength. In this example, the second light can be an idler light. A third light of a third wavelength travels in a third loop within main nonlinear optical waveguide **1402** and second extension optical waveguide **1406** in which the third loop has a third length for the third light of the third wavelength. In this example, the third light can be a pump light.

With reference to **Figure 15**, an illustration of an optical waveguide structure is depicted in accordance with an illustrative embodiment. As depicted, optical waveguide structure **1500** comprises main nonlinear optical waveguide **1502**, signal loop extension optical waveguide **1504**, and idler loop extension optical waveguide **1506**. In this illustrative example, main nonlinear optical waveguide **1502**, signal loop extension optical waveguide **1504** and idler loop extension optical waveguide **1506** are comprised of nonlinear material.

Light can propagate through the optical waveguides in optical waveguide structure **1500**. For example, light comprising a pump light, a signal light, and an idler light can propagate through one or more of main nonlinear optical waveguide **1502**, signal loop extension optical waveguide **1504**, and idler loop extension optical waveguide **1506**. In this illustrative example, optical waveguide structure **1500** incorporates one or more nonlinear optical processes that generate at least one of a signal light or an idler light using a pump light input into optical waveguide structure **1500** through pump input waveguide **1508**.

In this illustrative example, optical waveguide structure **1500** also has signal output waveguide **1510** and idler output waveguide **1512**. Pump input waveguide **1508** operates to input a pump light into main nonlinear optical waveguide **1502**. As depicted, signal output waveguide **1510** operates to output a signal light from signal loop extension optical waveguide **1504**, and idler output waveguide **1512** operates to output an idler light from idler loop extension optical waveguide **1506**.

In this illustrative example, optical waveguide structure **1500** also includes electrode **1514**, electrode **1516**, and electrode **1518**. These electrodes can operate to apply control signals in the form of voltages or currents to adjust the phases of one or more of the different wavelengths of light traveling through optical waveguide structure **1500**.

Optical waveguide structure **1500** can be implemented using one or more of the optical waveguide structures such as the optical waveguide structures depicted in cross-sectional form in **Figure 3** and **Figures 7-13**. For example, area **1520** includes main nonlinear optical waveguide **1502**. In this example, area **1520** can have a cross-sectional structure as shown for nonlinear optical waveguide **300** in **Figure 3**.

As another example, area **1522** contains main nonlinear optical waveguide **1502** and signal loop extension optical waveguide **1504**. This area can have a cross-sectional structure as shown for optical waveguide structure **900** in **Figure 9** or for optical waveguide structure **1100** in **Figure 11** and can form a first wavelength selected coupler. Area **1524** contains main nonlinear optical waveguide **1502** and idler loop extension optical waveguide **1506**. As illustrated, area **1524** can also have a cross-sectional structure as shown for

optical waveguide structure **900** in **Figure 9** or for optical waveguide structure **1100** in **Figure 11** and can form a second wavelength selected coupler.

In this depicted example, area **1526** includes main nonlinear optical waveguide **1502** and electrode **1516**. This area can have a cross-sectional structure as shown for optical waveguide structure **700** in **Figure 7** using a single tuning electrode.

As depicted, area **1540** is an optical coupler for coupling a signal light from main nonlinear optical waveguide **1502** to pump input waveguide **1508**. This area can have a cross-sectional structure as shown for optical waveguide structure **1000** in **Figure 10**.

With reference now to **Figure 16**, an illustration of a flowchart of a process for moving light through an optical waveguide structure is depicted in accordance with an illustrative embodiment. The process in **Figure 16** can be implemented in a physical waveguide structure such as nonlinear optical waveguide **102** in **Figures 1** and **2**. This process can also be implemented using the different optical waveguides shown in **Figure 3** and **Figures 7-13** in the different physical implementation shown in the different illustrative examples.

The process begins by inputting a light at a pump wavelength into a nonlinear optical waveguide structure having a central region within the nonlinear optical waveguide, wherein the central region comprises a nonlinear optical material, a first side region on a first side of the central region, and a second side region on a second side of the central region, wherein the central region has a first nonlinear coefficient that is larger than a second nonlinear coefficient of the first side region and the second side region (operation **1600**).

The process propagates the light at the pump wavelength along a path in the optical waveguide structure (operation **1602**). The process terminates thereafter. In operation **1602**, light generation occurs in the nonlinear optical waveguide.

The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatuses and methods in an illustrative embodiment. In this regard, each block in the flowcharts or block diagrams can represent at least one of a module, a segment, a function, or a portion of an operation or step. For example, one or more of the blocks can be implemented hardware, or a combination of the program code and hardware. When implemented in hardware, the hardware can, for example, take the form of integrated circuits that are manufactured or configured to perform one or more operations in the flowcharts or block diagrams. When implemented in software, the software can be used to simulate optical waveguide structures. When implemented as a combination of program code and hardware, the implementation may take the form of firmware. Each block in the flowcharts or the block diagrams can be implemented using special purpose hardware systems that perform the different operations or combinations of special purpose hardware and program code run by the special purpose hardware.

In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be performed substantially concurrently, or the blocks may sometimes be performed in the reverse order, depending upon the functionality involved. Also,

other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.

Turning now to **Figure 17**, an illustration of a block diagram of a product management system is depicted in accordance with an illustrative embodiment. Product management system **1700** is a physical hardware system. In this illustrative example, product management system **1700** includes at least one of manufacturing system **1702** or maintenance system **1704**.

Manufacturing system **1702** is configured to manufacture products. As depicted, manufacturing system **1702** includes manufacturing equipment **1706**. Manufacturing equipment **1706** includes at least one of fabrication equipment **1708** or assembly equipment **1710**.

Fabrication equipment **1708** is equipment that used to fabricate the nonlinear optical waveguide structure. Multiple copies or multiple versions of nonlinear optical waveguide structures can be fabricated on a substrate wafer. For example, different structures in nonlinear optical waveguides can be fabricated on the same substrate wafer. The substrate wafer can comprise a material such as silicon or lithium niobate or quartz or sapphire or silicon carbide.

Fabrication equipment **1708** can be used to fabricate a number of different structures. For example, fabrication equipment **1708** can be used to fabricate at least one of optical waveguide structures, nonlinear optical waveguides, laser transmitters, ultraviolet transmission systems, point-to-point communication devices, laser infrared countermeasure sources, through water optical communication devices, or other suitable devices, antennas, or other suitable types of parts or devices.

Fabrication equipment **1708** can include machines and tools. With respect to fabricating semiconductor components and optical waveguide components, fabrication equipment **1708** can comprise at least one of an epitaxial reactor, an oxidation system, a diffusion system, an etching system, a cleaning system, a bonding machine, a dicing machine, a wafer saw, an ion implantation system, a physical vapor deposition system, a chemical vapor deposition system, a photolithography system, an electron-beam lithography system, a plasma etcher, a die attachment machine, a wire bonder, a die overcoat system, molding equipment, a hermetic sealer, an electrical tester, a burn-in oven, a retention bake oven, a UV erase system, or other suitable types of equipment that can be used to manufacture semiconductor structures.

Assembly equipment **1710** is equipment used to assemble parts to form a product such as a chip, an integrated circuit, a sensor, an optical transmitter, an optical receiver, a computer, an aircraft, or some other product. Assembly equipment **1710** also can include machines and tools. These machines and tools may be at least one of a robotic arm, a spinner system, a sprayer system, an elevator system, a rail-based system, or a robot.

In this illustrative example, maintenance system **1704** includes maintenance equipment **1712**. Maintenance equipment **1712** can include any equipment needed to perform maintenance on and evaluation of a product. Maintenance equipment **1712** may include tools for performing different operations on parts on a product. These operations can include at least one of disassembling parts, refurbishing parts, inspecting parts, reworking parts, manufacturing replacement parts, or other operations for performing maintenance on the

product. These operations can be for routine maintenance, inspections, upgrades, refurbishment, or other types of maintenance operations.

In the illustrative example, maintenance equipment **1712** may include optical inspection devices, x-ray imaging systems, surface-profile measurement systems, drills, vacuum leak checkers, and other suitable devices. In some cases, maintenance equipment **1712** can include fabrication equipment **1708**, assembly equipment **1710**, or both to produce and assemble parts that needed for maintenance.

Product management system **1700** also includes control system **1714**. Control system **1714** is a hardware system and may also include software or other types of components. Control system **1714** is configured to control the operation of at least one of manufacturing system **1702** or maintenance system **1704**. In particular, control system **1714** can control the operation of at least one of fabrication equipment **1708**, assembly equipment **1710**, or maintenance equipment **1712**.

The hardware in control system **1714** can be implemented using hardware that may include computers, circuits, networks, and other types of equipment. The control may take the form of direct control of manufacturing equipment **1706**. For example, robots, computer-controlled machines, and other equipment can be controlled by control system **1714**. In other illustrative examples, control system **1714** can manage operations performed by human operators **1716** in manufacturing or performing maintenance on a product. For example, control system **1714** can assign tasks, provide instructions, display models, or perform other operations to manage operations performed by human operators **1716**. In these illustrative examples, the different processes

for fabricating semiconductor structures, optical structures, nonlinear optical waveguides, laser transmitters, photon generators, photon transmitters, photon detectors, ultraviolet transmission systems, point-to-point communication devices, laser infrared countermeasure sources, through water optical communication devices, or other suitable devices can be manufactured using processes implemented in control system **1714**.

In the different illustrative examples, human operators **1716** can operate or interact with at least one of manufacturing equipment **1706**, maintenance equipment **1712**, or control system **1714**. This interaction can occur to manufacture semiconductor structures and other components for products such as semiconductor devices, optical waveguides, or other components for use in products such as aircraft, spacecraft, communications systems, computation systems, and sensor systems.

Further, control system **1714** can be used to adjust manufacturing of nonlinear optical waveguides, optical waveguides, optical couplers and terminations dynamically during the manufacturing process. For example, many points in the process of fabricating the optical waveguide structure including the nonlinear optical waveguide as well as other components are present at which adjustments can be made to control characteristics of components in an optical waveguide structure.

The dimensions of the fabricated core region can be measured, and optical waveguide design simulations can be performed to determine the values of the effective refractive indices that can be obtained for various candidate values of the upper cladding height. The upper cladding height that gives the desired value for the phase walk-off can be chosen accordingly. Upper cladding

material can then be deposited that has the desired thickness or height.

Another point in the fabrication process is after the upper cladding material has been deposited to a value that is greater than what might be desired. Test devices such as asymmetric Mach-Zehnder interferometers and micro-ring resonators can be fabricated in addition to the nonlinear optical waveguide.

These test devices can be characterized to extract values for the effect refractive indices for the upper cladding height of those test devices. The upper cladding height can then be reduced by etching away some of the upper cladding material, possibly in an iterative manner accompanied by additional measurements of the test structures. In this way, the desired value for the upper cladding height can be approached and then achieved.

Thus, the illustrative embodiments provide a method, apparatus, and system for propagating light in an optical waveguide structure. In one illustrative example, an optical waveguide structure comprises a nonlinear optical waveguide, a central region, a first side region, and a second side region. The central region is located within the nonlinear optical waveguide, wherein the central region comprises a nonlinear optical material. The first side region is on a first side of the central region and the second side region is on a second side of the central region. The central region has a first nonlinear coefficient that is larger than a second nonlinear coefficient of the first side region and the second side region.

The configuration of the core region containing the central region and the two side regions can be made in a manner that increases the generation of light by the optical waveguide structure. The different dimensions

can be selected to increase the efficiency and light generation in the different illustrative examples.

Thus, illustrative embodiments provide a method, apparatus, system for a cross-section in an optical waveguide has desired characteristics in at least one of light propagation or light generation. In one illustrative example, an optical waveguide structure comprises a nonlinear optical waveguide with a central region, a first side region, and a second side region located within the nonlinear optical waveguide. The central region comprises a nonlinear optical material. The first side region is located on a first side of the central region. The second side region is located on a second side of the central region. The central region has a first nonlinear coefficient that is larger than a second nonlinear coefficient of the first side region and the second side region. The central region, the first side region, and the second side region form a core region within the nonlinear optical waveguide.

In one illustrative example, the different structures in the core region can be designed in a manner that provides at least one of the design propagation or light generation within the nonlinear optical waveguide. The design can include a selection of at least one of a material or a dimension for the different components in the core region. As another example, the dimensions the core region as a whole can be selected. In yet another illustrative example, other structures can be included in the nonlinear optical waveguide such as a cladding, another core region, or other suitable components.

Some features of the illustrative examples are described in the following clauses. These clauses are examples of features not intended to limit other illustrative examples.

Further, the disclosure comprises embodiments according to the following clauses:

Clause 1:

An optical waveguide structure comprising:

a nonlinear optical waveguide;

a central region within the nonlinear optical waveguide, wherein the central region comprises a nonlinear optical material having a first nonlinear coefficient;

a first side region on a first side of the central region; and

a second side region on a second side of the central region, wherein the nonlinear optical material comprising the central region has the first nonlinear coefficient that is larger than a second nonlinear coefficient of a second material comprising the first side region and the second side region.

Clause 2:

The optical waveguide structure according to clause 1, wherein the central region has a set of dimensions selected to increase a light generation within the optical waveguide structure.

Clause 3:

The optical waveguide structure according to clause 2, wherein the light generation increases for at least one of a signal light or an idler light when a pump light travels through the nonlinear optical waveguide.

Clause 4:

The optical waveguide structure according any of clauses 2-3, wherein the set of dimensions is a width selected to increase an overlap of an electromagnetic field for a light of interest with the central region and the electromagnetic field for the light of interest has a second sign in the first side region and the second side

region such that light generation is increased in the nonlinear optical waveguide.

Clause 5:

The optical waveguide structure according to clause 2, wherein the set of dimensions is selected from least one of a width, a height, or a sidewall slope.

Clause 6:

The optical waveguide structure according any of clauses 1-5, wherein the second nonlinear coefficient is selected such that the first side region and the second side region have a reduced contribution to light generation.

Clause 7:

The optical waveguide structure according to any of clauses 1-6, wherein the second nonlinear coefficient is selected such that a nonlinear optical interaction in the nonlinear optical waveguide is reduced to about zero.

Clause 8:

The optical waveguide structure according to any of clauses 1-7, wherein a pump light traveling in the optical waveguide structure has an electromagnetic field that has a first sign in the central region while having a second sign in the first side region and the second side region.

Clause 9:

The optical waveguide structure according to any of clauses 1-8, wherein a cross-section of the central region, the first side region, and the second side region has at least one of a strip width or a strip height that is selected to cause a phase matching condition.

Clause 10:

The optical waveguide structure according to any of clauses 1-9, wherein the central region, the first side

region and the second side region form a core region, the optical waveguide structure further comprising:

a cladding region comprising a dielectric material, wherein the core region is located within the cladding region.

Clause 11:

The optical waveguide structure according to clause 10, wherein the dielectric material is selected from at least one of a silicon dioxide, a polymer, or air.

Clause 12:

The optical waveguide structure according to any preceding clause, wherein the nonlinear optical material is a first nonlinear optical material that has a first second order nonlinear coefficient with a magnitude that is at least one picometer/volt, and wherein the first side region and the second side region have a second nonlinear optical material that has a second second-order nonlinear coefficient whose magnitude is equal to or less than one third the magnitude of the first second order nonlinear coefficient for the first nonlinear optical material.

Clause 13:

The optical waveguide structure according to any of clauses 1-12, wherein the central region is comprised of at least one of lithium niobate ($LiNbO_2$), silicon carbide, aluminum nitride, gallium nitride, gallium aluminum nitride, gallium phosphide, gallium aluminum phosphide, aluminum phosphide, gallium arsenide, gallium aluminum arsenide, or aluminum arsenide.

Clause 14:

The optical waveguide structure according to any of clauses 1-13, wherein the second material in the first side region and the second side region are comprised of a material such that a nonlinear optical process in the

first side region and the second side region does not generate light.

Clause 15:

The optical waveguide structure according to any of clauses 1-14, wherein the first side region and the second side region are comprised of at least one of silicon nitride, titanium dioxide silicon, silicon oxynitride, or hafnia.

Clause 16:

The optical waveguide structure according to any of clauses 1-15, wherein the nonlinear optical waveguide is a main nonlinear optical waveguide, the optical waveguide structure further comprising:

a first extension optical waveguide;

a second extension optical waveguide;

a first wavelength selective coupler that couples the main nonlinear optical waveguide and the first extension optical waveguide to each other such that a second light of a second wavelength is coupled between the main nonlinear optical waveguide and the first extension optical waveguide; and

a second wavelength selective coupler that couples the main nonlinear optical waveguide and the second extension optical waveguide to each other such a third light of a third wavelength is coupled between the main nonlinear optical waveguide and the second extension optical waveguide.

Clause 17:

The optical waveguide structure according to clause 16, wherein the second light of the second wavelength travels in a second loop within the main nonlinear optical waveguide and the first extension optical waveguide in which the second loop has a second length for the second light of the second wavelength, and

wherein the third light of the third wavelength travels in a third loop within the main nonlinear optical waveguide and the second extension optical waveguide in which the third loop has a third length for the third light of the third wavelength.

Clause 18:

The optical waveguide structure according to clause 16, wherein the first wavelength selective coupler is a starting first extension wavelength selective coupler located at a first extension starting location in the main nonlinear optical waveguide and the first extension optical waveguide and the second wavelength selective coupler is a starting second extension wavelength selective coupler located at a second extension starting location in the main nonlinear optical waveguide and the second extension optical waveguide, the optical waveguide structure further comprising:

an ending first extension wavelength selective coupler located in an ending first extension location in the main nonlinear optical waveguide and the first extension optical waveguide; and

an ending second extension wavelength selective coupler located at an ending second extension location in the main nonlinear optical waveguide and the second extension optical waveguide.

Clause 19:

The optical waveguide structure according any of clauses 1-18 further comprising:

a set of electrodes in a location selected from at least one of adjacent to the first side region, adjacent to the second side region, adjacent to the central region.

Clause 20:

The optical waveguide structure according any of clauses 1-19, wherein the central region, the first side

region and the second side region form a first core region and further comprising:

a second core region.

Clause 21:

The optical waveguide structure according to clause 20, wherein a gap is present between the first core region and the second core region.

Clause 22:

A method for moving a light through a nonlinear optical waveguide structure:

inputting a light at a pump wavelength into the nonlinear optical waveguide structure having a central region within a nonlinear optical waveguide in nonlinear optical waveguide structure, wherein the central region comprises a nonlinear optical material, a first side region of a first side of the central region, and a second side region on a second side of the central region, wherein the central region has a first nonlinear coefficient that is larger than a second nonlinear coefficient of the first side region and the second side region; and

propagating the light at the pump wavelength along a path in the optical waveguide structure, wherein light generation occurs in the nonlinear optical waveguide.

Clause 23:

The method of according to clause 22, wherein the central region has a set of dimensions selected to increase a light generation in the optical waveguide structure.

Clause 24:

The method according to clause 23, wherein the light generation increases for at least one of a signal light or an idler light when a pump light overlaps the central region of the nonlinear optical waveguide.

Clause 25:

The method according to clause 23, wherein the set of dimensions is a width selected to increase an overlap of an electromagnetic field has a first sign for a light of interest with the central region and the electromagnetic field for the light of interest has a second sign in the first side region and the second side region such that light generation is increased within the nonlinear optical waveguide.

Clause 26:

The method according to any of clause 23-25, wherein the set of dimensions is selected from least one of a width or a height.

The description of the different illustrative embodiments has been presented for purposes of illustration and description and is not intended to be exhaustive or limited to the embodiments in the form disclosed. The different illustrative examples describe components that perform actions or operations. In an illustrative embodiment, a component can be configured to perform the action or operation described. For example, the component can have a configuration or design for a structure that provides the component an ability to perform the action or operation that is described in the illustrative examples as being performed by the component. Further, to the extent that terms "includes", "including", "has", "contains", and variants thereof are used herein, such terms are intended to be inclusive in a manner similar to the term "comprises" as an open transition word without precluding any additional or other elements.

Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different features as compared to other desirable embodiments. The

embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

CLAIMS:

What is claimed is:

1. An optical waveguide structure (100) comprising:

a nonlinear optical waveguide (102);

a central region (114) within the nonlinear optical waveguide (102), wherein the central region (114) comprises a nonlinear optical material (104) having a first nonlinear coefficient (124);

a first side region (116) on a first side (120) of the central region (114); and

a second side region (118) on a second side (122) of the central region (114), wherein the nonlinear optical material (104) comprising the central region (114) has the first nonlinear coefficient (124) that is larger than a second nonlinear coefficient (126) of a second material (119) comprising the first side region (116) and the second side region (118).

2. The optical waveguide structure (100) of claim 1, wherein the central region (114) has a set of dimensions (130) selected to increase a light generation (128) within the optical waveguide structure (100).

3. The optical waveguide structure (100) of claim 2, wherein the light generation (128) increases for at least one of a signal light (110) or an idler light (112) when a pump light (108) travels through the nonlinear optical waveguide (102).

4. The optical waveguide structure (100) of any of claims 2-3, wherein the set of dimensions (130) is a width (132) selected to increase an overlap of an

electromagnetic field for a light of interest with the central region (114) and the electromagnetic field for the light of interest has a second sign in the first side region (116) and the second side region (118) such that light generation (128) is increased in the nonlinear optical waveguide (102).

5. The optical waveguide structure (100) of claim 2, wherein the set of dimensions (130) is selected from least one of a width (132), a height (134), or a sidewall slope (135).

6. The optical waveguide structure (100) of any of claims 1-5, wherein the second nonlinear coefficient (126) is selected such that the first side region (116) and the second side region (118) have a reduced contribution to light generation (128).

7. The optical waveguide structure (100) of any of claims 1-6, wherein the second nonlinear coefficient (126) is selected such that a nonlinear optical interaction in the nonlinear optical waveguide (102) is reduced to about zero.

8. The optical waveguide structure (100) of any of claims 1-7, wherein a pump light (108) traveling in the optical waveguide structure (100) has an electromagnetic field that has a first sign in the central region (114) while having a second sign in the first side region (116) and the second side region (118).

9. The optical waveguide structure (100) of any of claims 1-8, wherein a cross-section of the central region (114), the first side region (116), and the second side

region (118) has at least one of a strip width or a strip height that is selected to cause a phase matching condition.

10. The optical waveguide structure (100) of any of claims 1-9, wherein the central region (114), the first side region (116) and the second side region (118) form a core region (200), the optical waveguide structure (100) further comprising:

a cladding region (201) comprising a dielectric material, wherein the core region (200) is located within the cladding region (201).

11. The optical waveguide structure (100) of claim 10, wherein the dielectric material is selected from at least one of a silicon dioxide, a polymer, or air.

12. The optical waveguide structure (100) of any of claims 1-11, wherein the nonlinear optical material (104) is a first nonlinear optical material (104) that has a first second order nonlinear coefficient with a magnitude that is at least one picometer/volt, and wherein the first side region (116) and the second side region (118) have a second nonlinear optical material (104) that has a second second-order nonlinear coefficient whose magnitude is equal to or less than one third the magnitude of the first second order nonlinear coefficient for the first nonlinear optical material (104).

13. The optical waveguide structure (100) of any of claims 1-12, wherein the central region (114) is comprised of at least one of lithium niobate ($LiNbO_2$), silicon carbide, aluminum nitride, gallium nitride, gallium aluminum nitride, gallium phosphide, gallium

aluminum phosphide, aluminum phosphide, gallium arsenide, gallium aluminum arsenide, or aluminum arsenide.

14. The optical waveguide structure (100) of any of claims 1-13, wherein the second material (119) in the first side region (116) and the second side region (118) are comprised of a material such that a nonlinear optical process in the first side region (116) and the second side region (118) does not generate light.

15. The optical waveguide structure (100) of any of claims 1-14, wherein the first side region (116) and the second side region (118) are comprised of at least one of silicon nitride, titanium dioxide silicon, silicon oxynitride, or hafnia.

16. The optical waveguide structure (100) of any of claims 1-15, wherein the nonlinear optical waveguide (102) is a main nonlinear optical waveguide (1402), the optical waveguide structure (100) further comprising:

a first extension optical waveguide (1404);

a second extension optical waveguide (1406);

a first wavelength selective coupler that couples the main nonlinear optical waveguide (102) and the first extension optical waveguide (1404) to each other such that a second light of a second wavelength is coupled between the main nonlinear optical waveguide (1402) and the first extension optical waveguide (1404); and

a second wavelength selective coupler that couples the main nonlinear optical waveguide (102) and the second extension optical waveguide (1406) to each other such a third light of a third wavelength is coupled between the main nonlinear optical waveguide (1402) and the second extension optical waveguide (1406).

17. The optical waveguide structure (100) of claim 16, wherein the second light of the second wavelength travels in a second loop within the main nonlinear optical waveguide (1402) and the first extension optical waveguide (1404) in which the second loop has a second length for the second light of the second wavelength, and wherein the third light of the third wavelength travels in a third loop within the main nonlinear optical waveguide (1402) and the second extension optical waveguide (1406) in which the third loop has a third length for the third light of the third wavelength.

18. The optical waveguide structure (100) of claim 16, wherein the first wavelength selective coupler is a starting first extension wavelength selective coupler located at a first extension starting location in the main nonlinear optical waveguide (1402) and the first extension optical waveguide (1404) and the second wavelength selective coupler is a starting second extension wavelength selective coupler located at a second extension starting location in the main nonlinear optical waveguide (1402) and the second extension optical waveguide (1406), the optical waveguide structure (100) further comprising:

an ending first extension wavelength selective coupler located in an ending first extension location in the main nonlinear optical waveguide (1402) and the first extension optical waveguide (1404); and

an ending second extension wavelength selective coupler located at an ending second extension location in the main nonlinear optical waveguide (1402) and the second extension optical waveguide (1406).

19. The optical waveguide structure (100) of any of claims 1-18 further comprising:

a set of electrodes (242) in a location selected from at least one of adjacent to the first side region (116), adjacent to the second side region (118), adjacent to the central region (114).

20. The optical waveguide structure (100) of any of claims 1-19, wherein the central region (114), the first side region (116) and the second side region (118) form a first core region (249, 914) and further comprising:

a second core region (250, 926).

21. The optical waveguide structure (100) of claim 20, wherein a gap (906) is present between the first core region (249, 914)) and the second core region (250, 926)).

22. A method for moving a light through a nonlinear optical waveguide (102) structure (100):

inputting (1100) a light at a pump wavelength into the nonlinear optical waveguide (102) structure (100) having a central region (114) within a nonlinear optical waveguide (102) in nonlinear optical waveguide (102) structure (100), wherein the central region (114) comprises a nonlinear optical material (104), a first side region (116) of a first side (120) of the central region (114), and a second side region (118) on a second side (122) of the central region (114), wherein the central region (114) has a first nonlinear coefficient (124) that is larger than a second nonlinear coefficient (126) of the first side region (116) and the second side region (118); and

propagating (1102) the light at the pump wavelength along a path in the optical waveguide structure (100), wherein light generation (128) occurs in the nonlinear optical waveguide (102).

23. The method of claim 22, wherein the central region (114) has a set of dimensions (130) selected to increase a light generation (128) in the optical waveguide structure (100).

24. The method of claim 23, wherein the light generation (128) increases for at least one of a signal light (110) or an idler light (112) when a pump light (108) overlaps the central region (114) of the nonlinear optical waveguide (102).

25. The method of claim 23, wherein the set of dimensions (130) is a width (132) selected to increase an overlap of an electromagnetic field has a first sign for a light of interest with the central region (114) and the electromagnetic field for the light of interest has a second sign in the first side region (116) and the second side region (118) such that light generation (128) is increased within the nonlinear optical waveguide (102).

26. The method of any of claims 23-25, wherein the set of dimensions (130) is selected from least one of a width (132) or a height (134).

FIG. 1

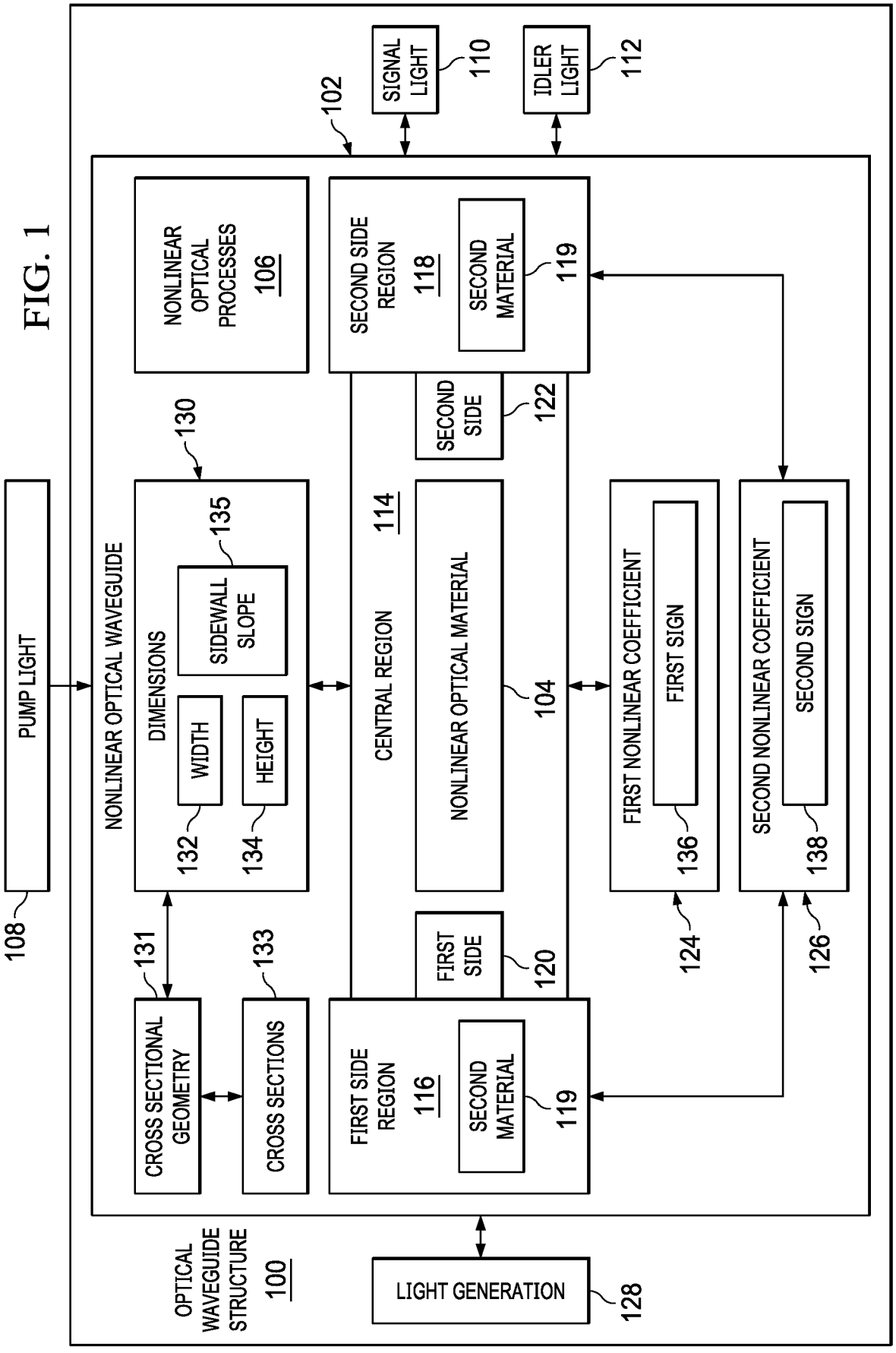
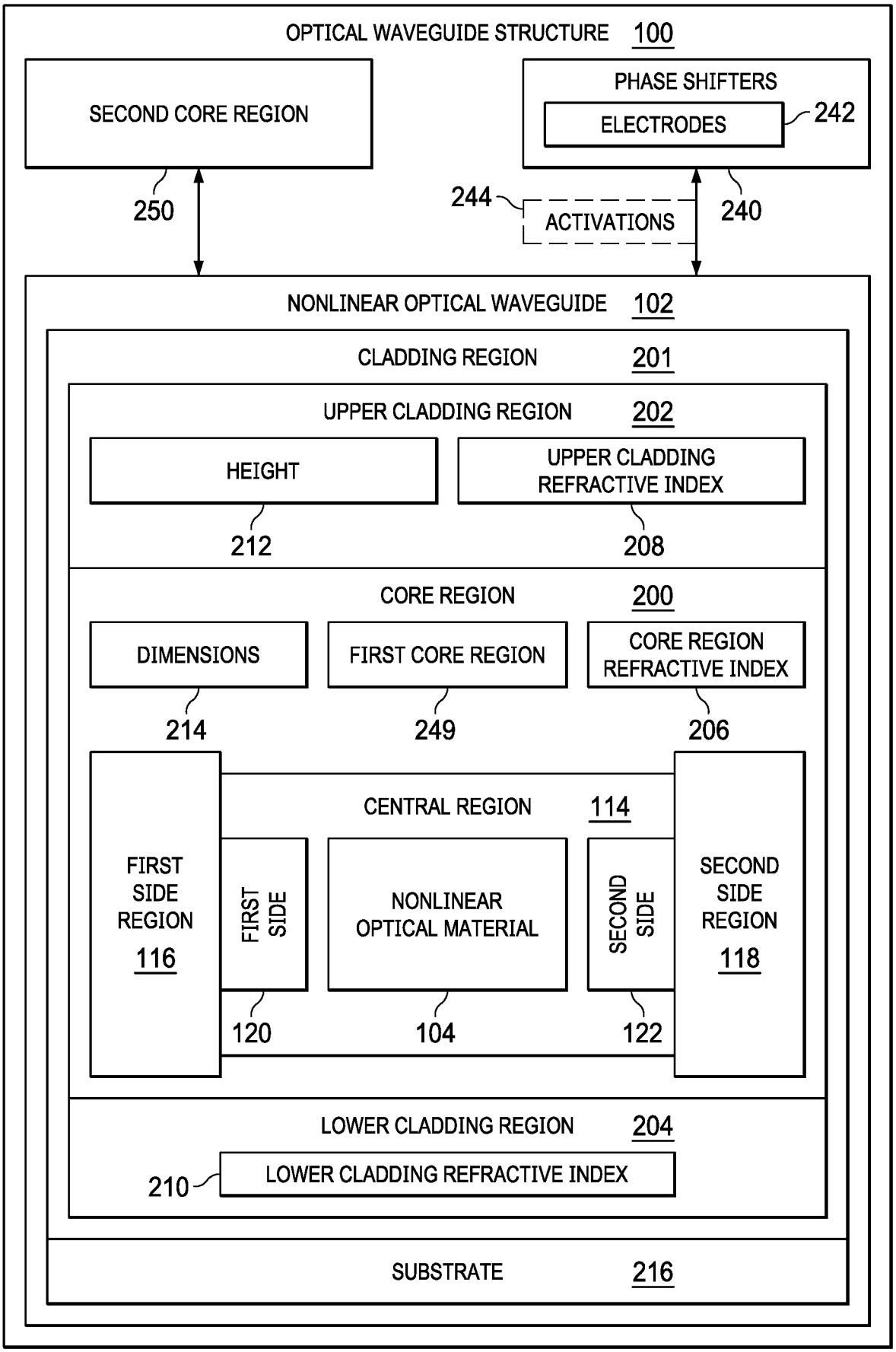

OPTICAL WAVEGUIDE STRUCTURE 100
NONLINEAR OPTICAL WAVEGUIDE
102
SIGNAL LIGHT
110
IDLER LIGHT
112
NONLINEAR OPTICAL PROCESSES 106
SECOND SIDE REGION 118
SECOND MATERIAL
119
SECOND SIDE
122
PUMP LIGHT
108
130
DIMENSIONS
WIDTH
132
HEIGHT
134
SIDEWALL SLOPE
135
CENTRAL REGION
114
NONLINEAR OPTICAL MATERIAL
104
FIRST NONLINEAR COEFFICIENT
FIRST SIGN
136
SECOND NONLINEAR COEFFICIENT
SECOND SIGN
138
131
CROSS SECTIONAL GEOMETRY
133
CROSS SECTIONS
FIRST SIDE
120
124
126
FIRST SIDE REGION 116
SECOND MATERIAL
119
LIGHT GENERATION
128

FIG. 2


OPTICAL WAVEGUIDE STRUCTURE 100
SECOND CORE REGION
PHASE SHIFTERS
ELECTRODES
242
250
244
ACTIVATIONS
240
NONLINEAR OPTICAL WAVEGUIDE 102
CLADDING REGION 201
UPPER CLADDING REGION 202
HEIGHT
UPPER CLADDING REFRACTIVE INDEX
212
208
CORE REGION 200
DIMENSIONS
FIRST CORE REGION
CORE REGION REFRACTIVE INDEX
214
249
206
CENTRAL REGION 114
FIRST SIDE REGION 116
FIRST SIDE
NONLINEAR OPTICAL MATERIAL
SECOND SIDE
SECOND SIDE REGION 118
120
104
122
LOWER CLADDING REGION 204
210
LOWER CLADDING REFRACTIVE INDEX
SUBSTRATE 216

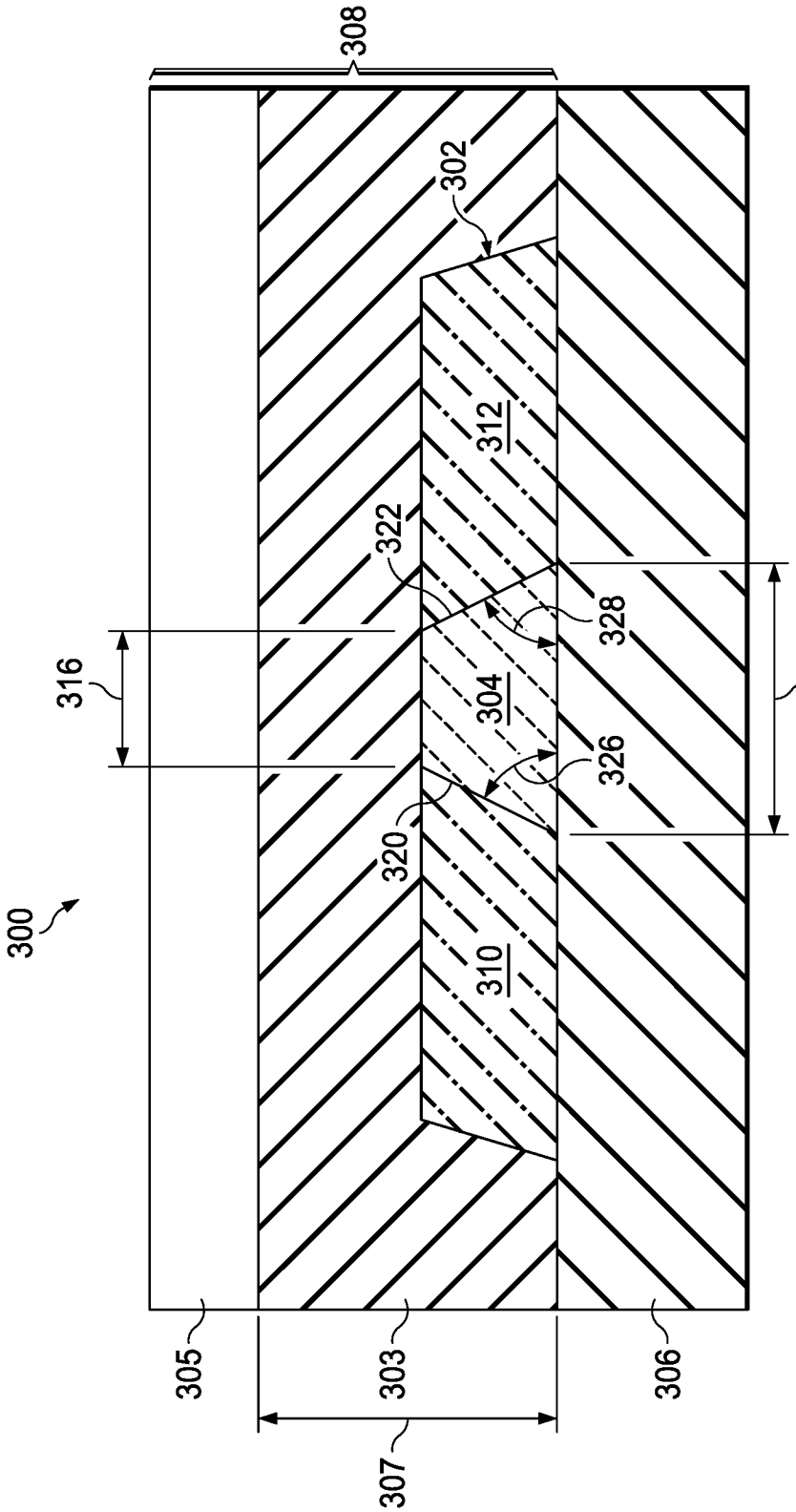


FIG. 3

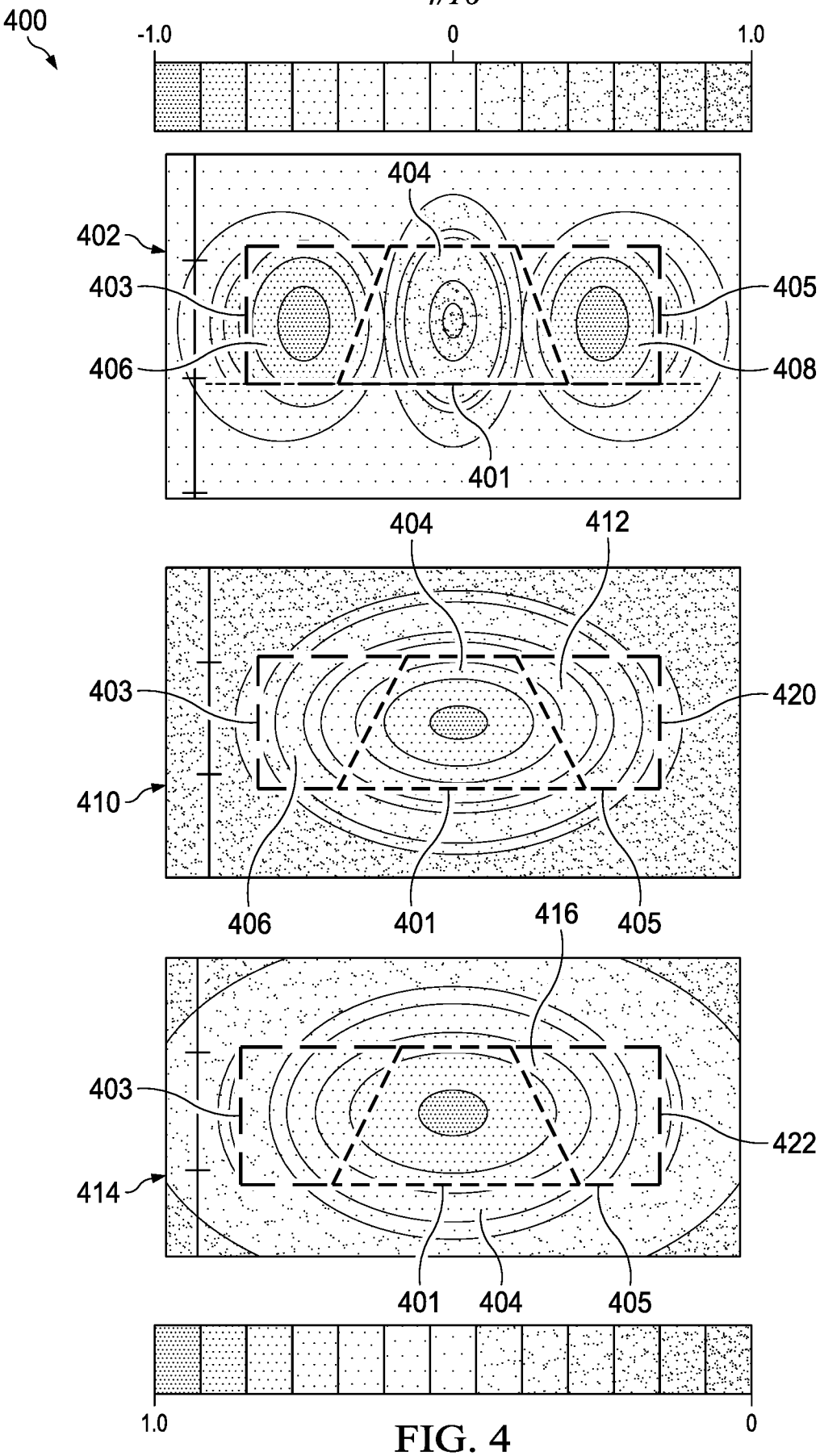

400
-1.0
0
1.0
404
402
403
405
406
408
401
404
412
403
420
410
406
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416
405
403
422
414
401
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405
1.0
0

FIG. 4

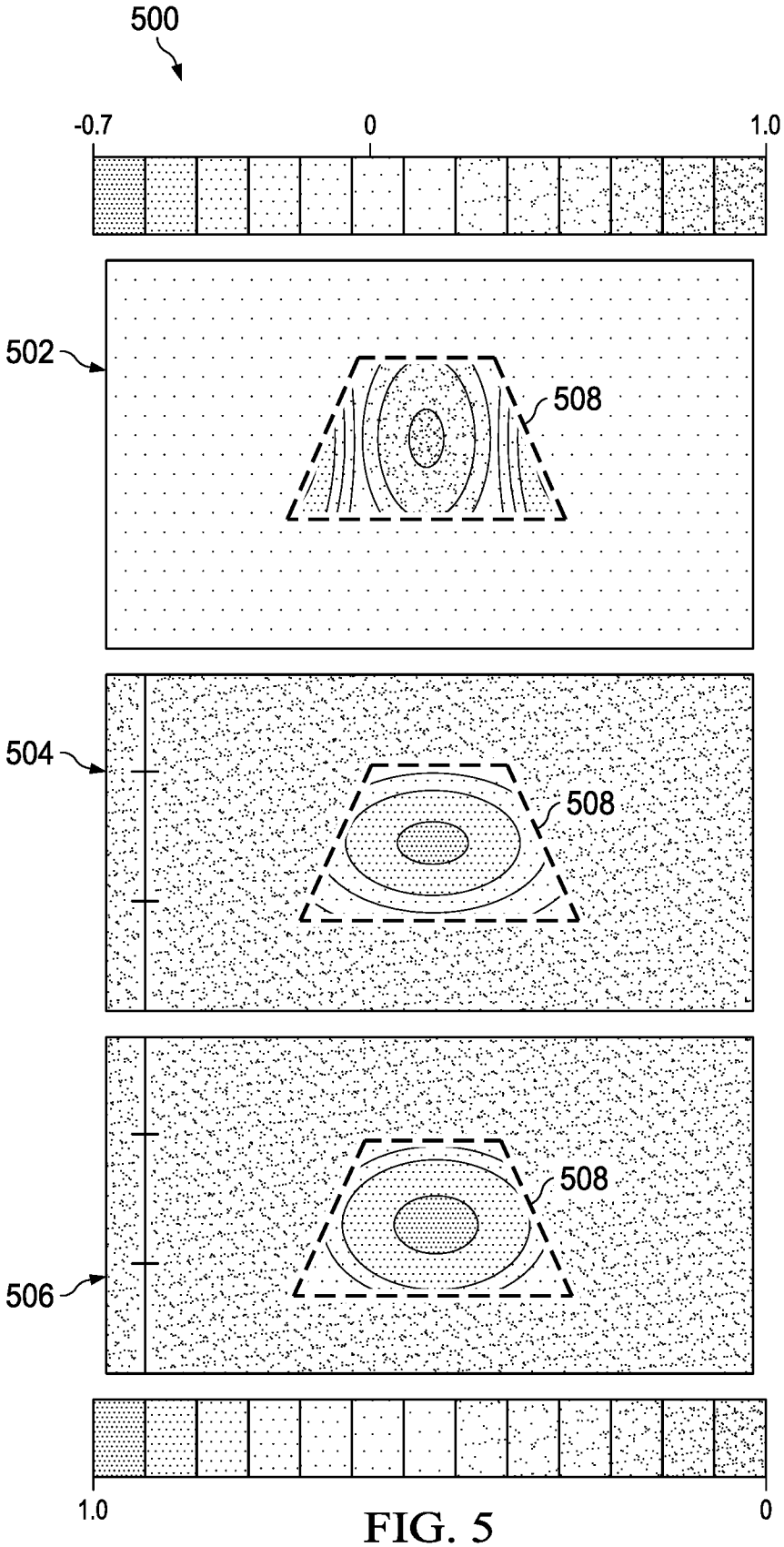
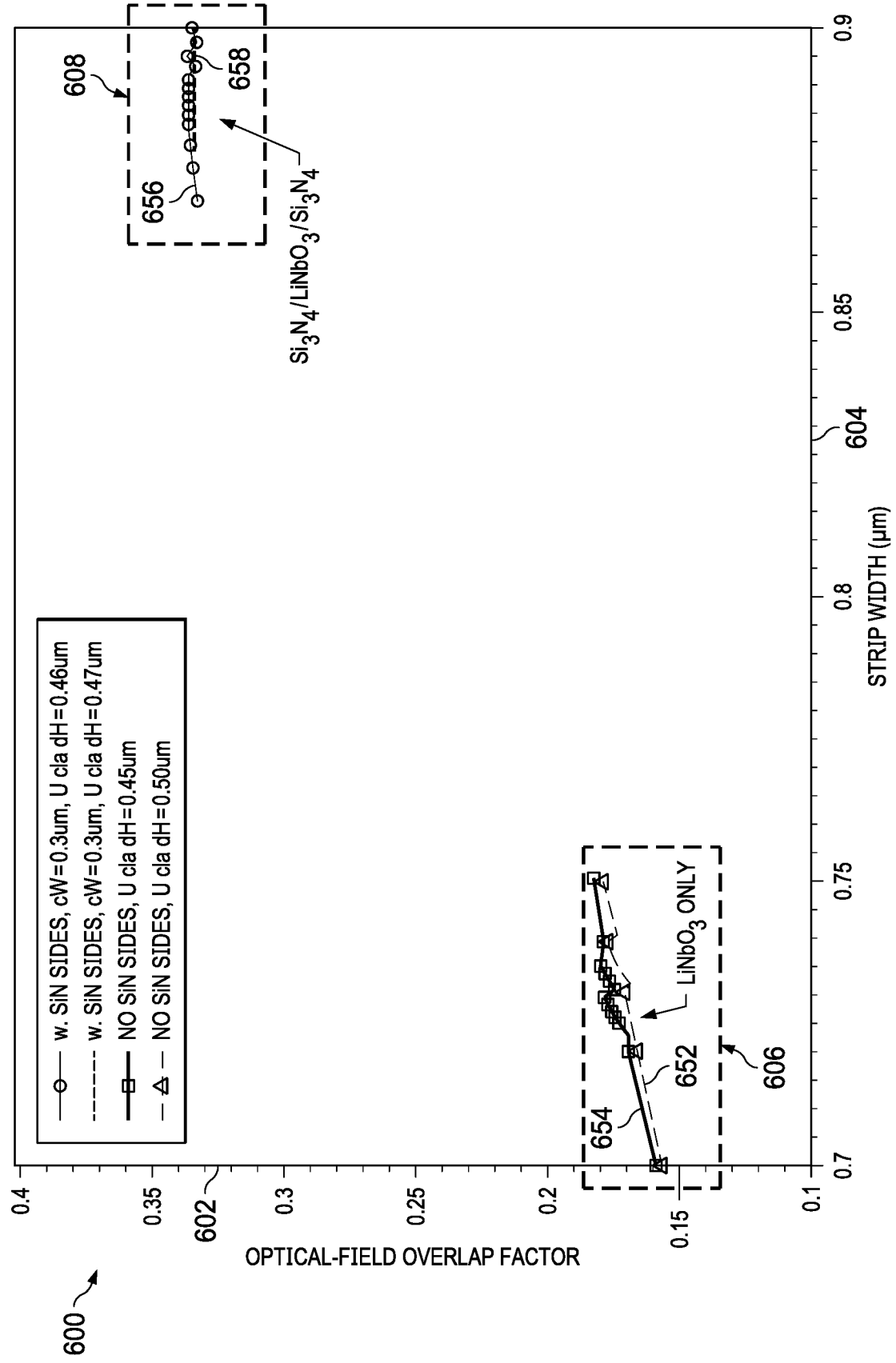


FIG. 5

FIG. 6


600
602
604
606
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652
654
656
658
w. SiN SIDES, cW=0.3um, U cla dH=0.46um
w. SiN SIDES, cW=0.3um, U cla dH=0.47um
NO SiN SIDES, U cla dH=0.45um
NO SiN SIDES, U cla dH=0.50um
$Si_3N_4/LiNbO_3/Si_3N_4$
$LiNbO_3$ ONLY
OPTICAL-FIELD OVERLAP FACTOR
STRIP WIDTH (μm)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.7
0.75
0.8
0.85
0.9

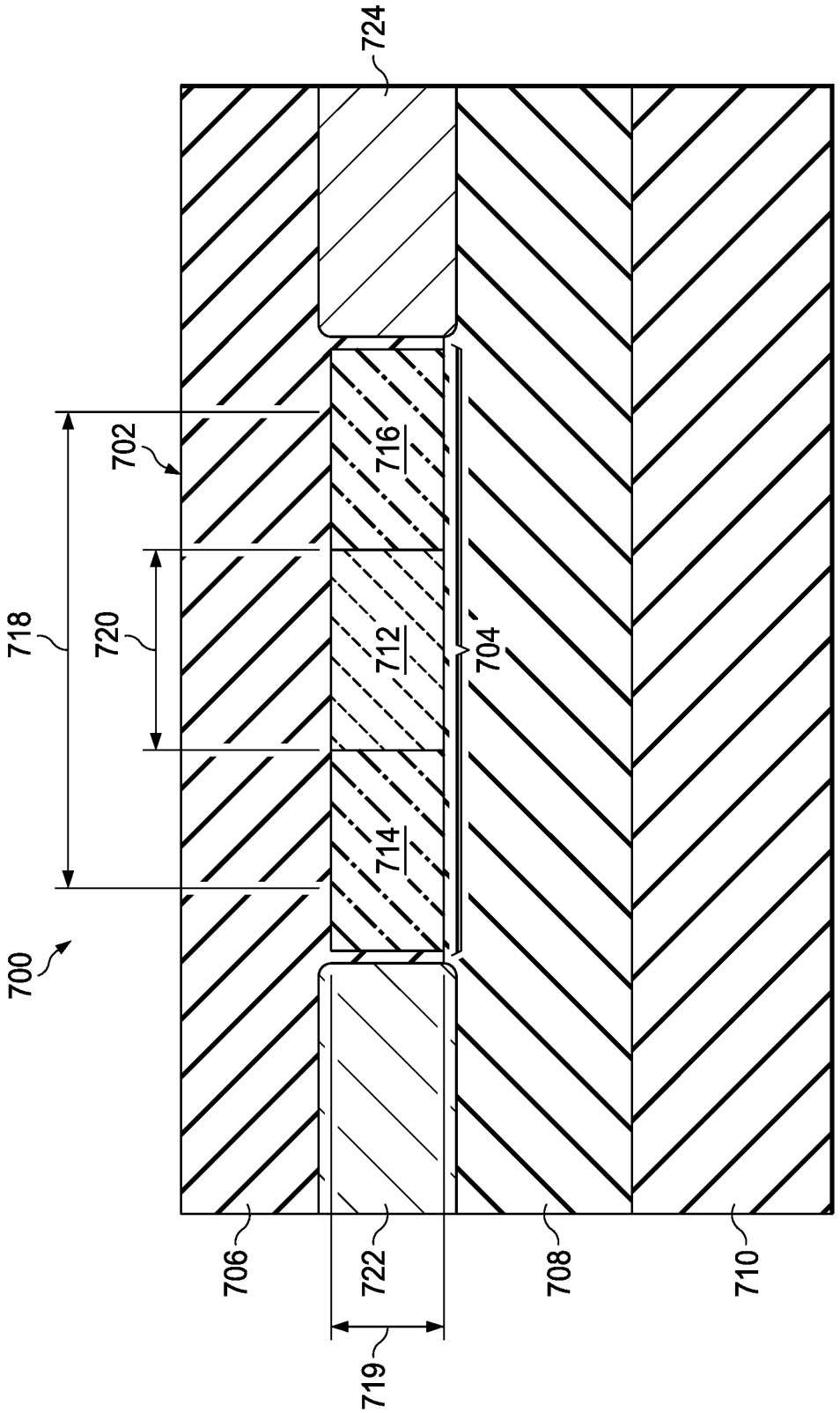


FIG. 7

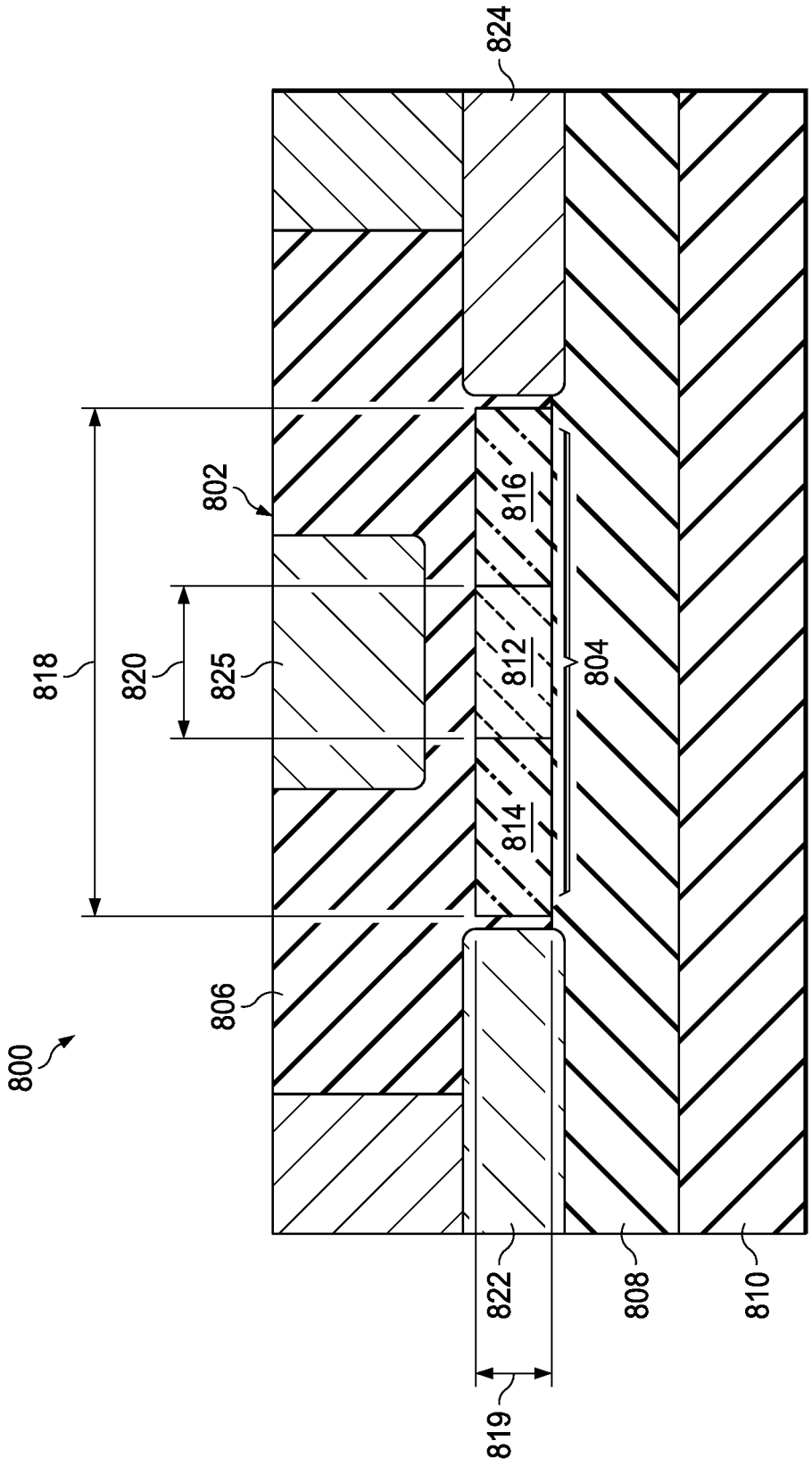


FIG. 8

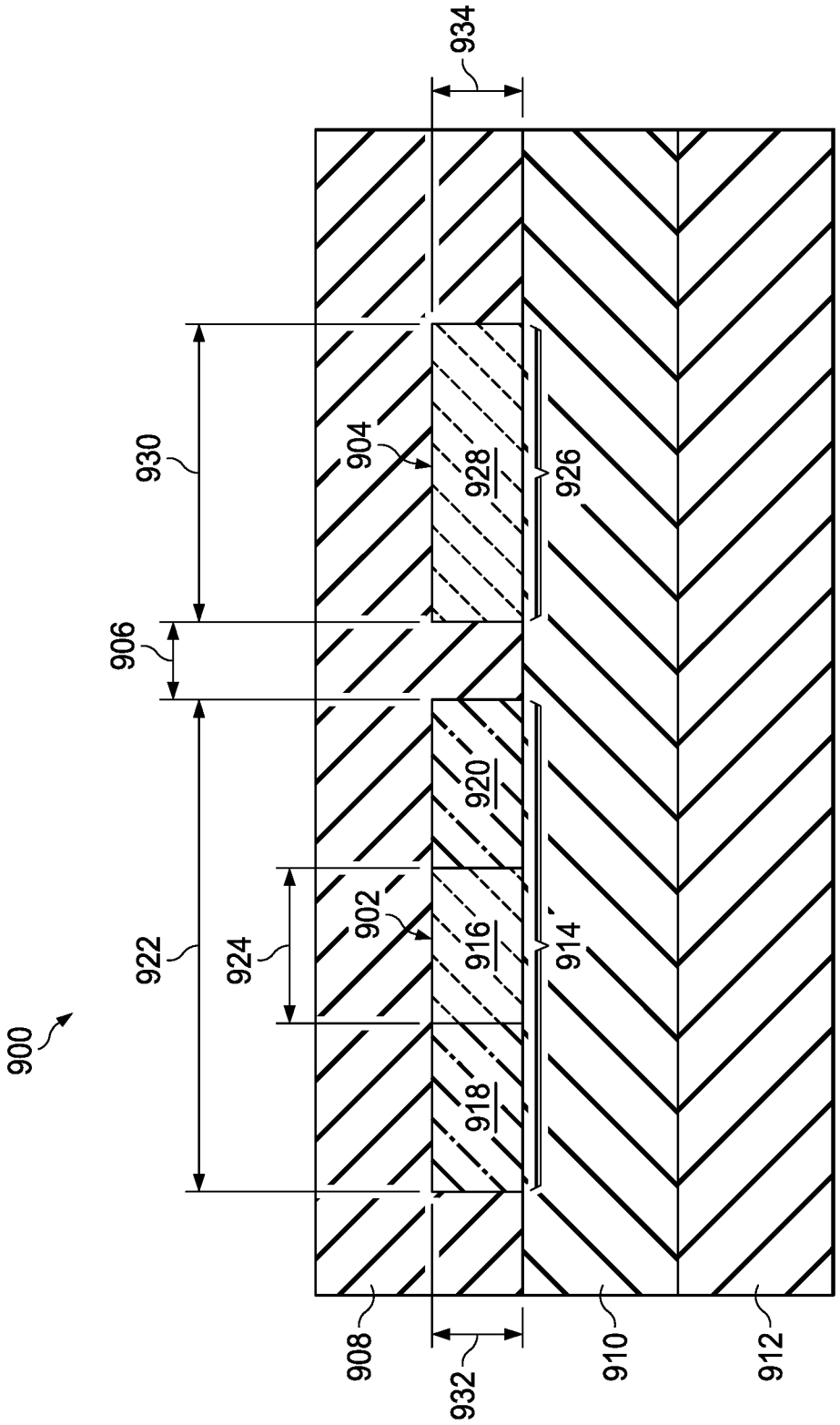

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FIG. 9

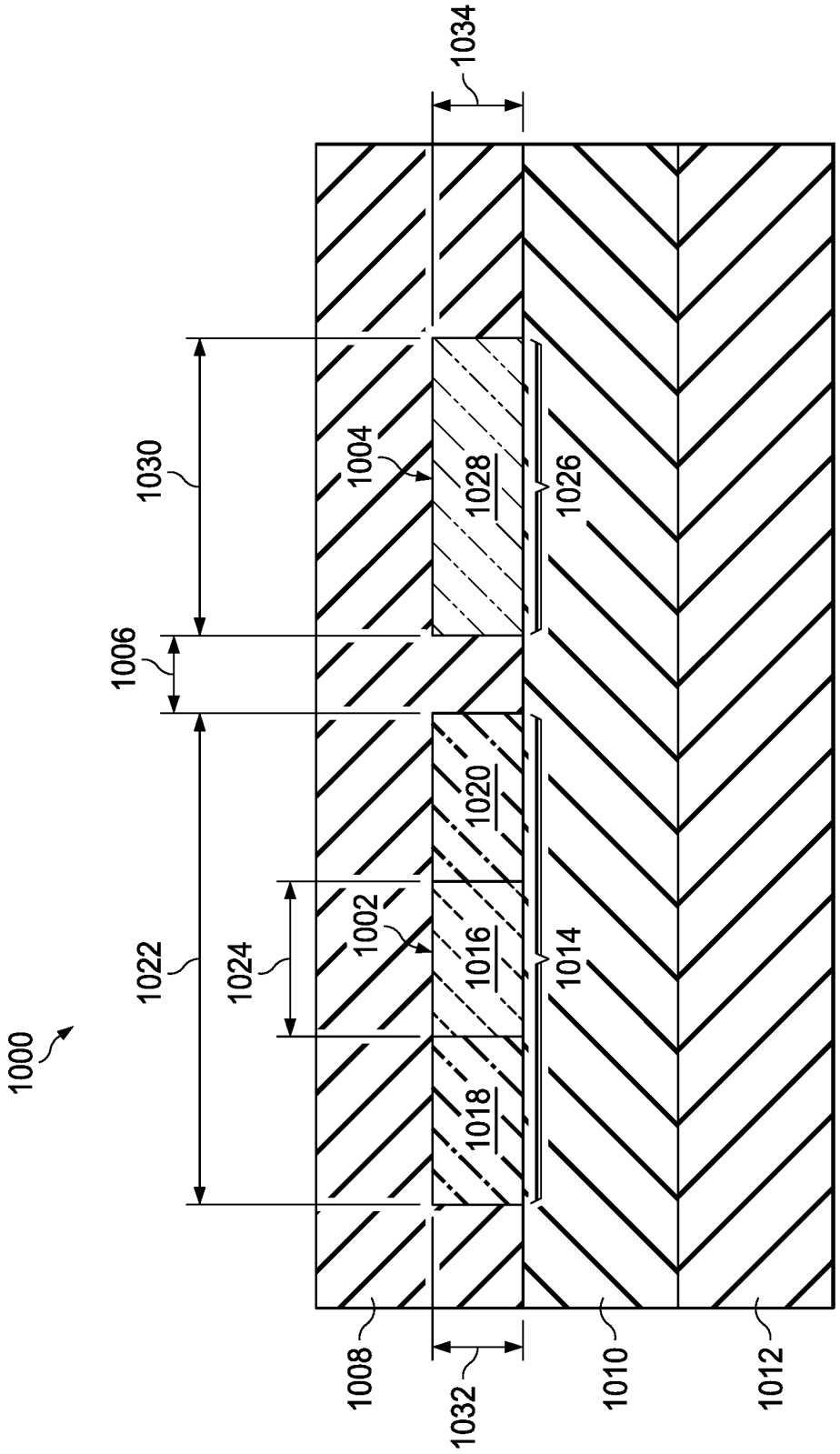

1034
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1004
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1022
1024
1002
1016
1014
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1018
1008
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1010
1012

FIG. 10

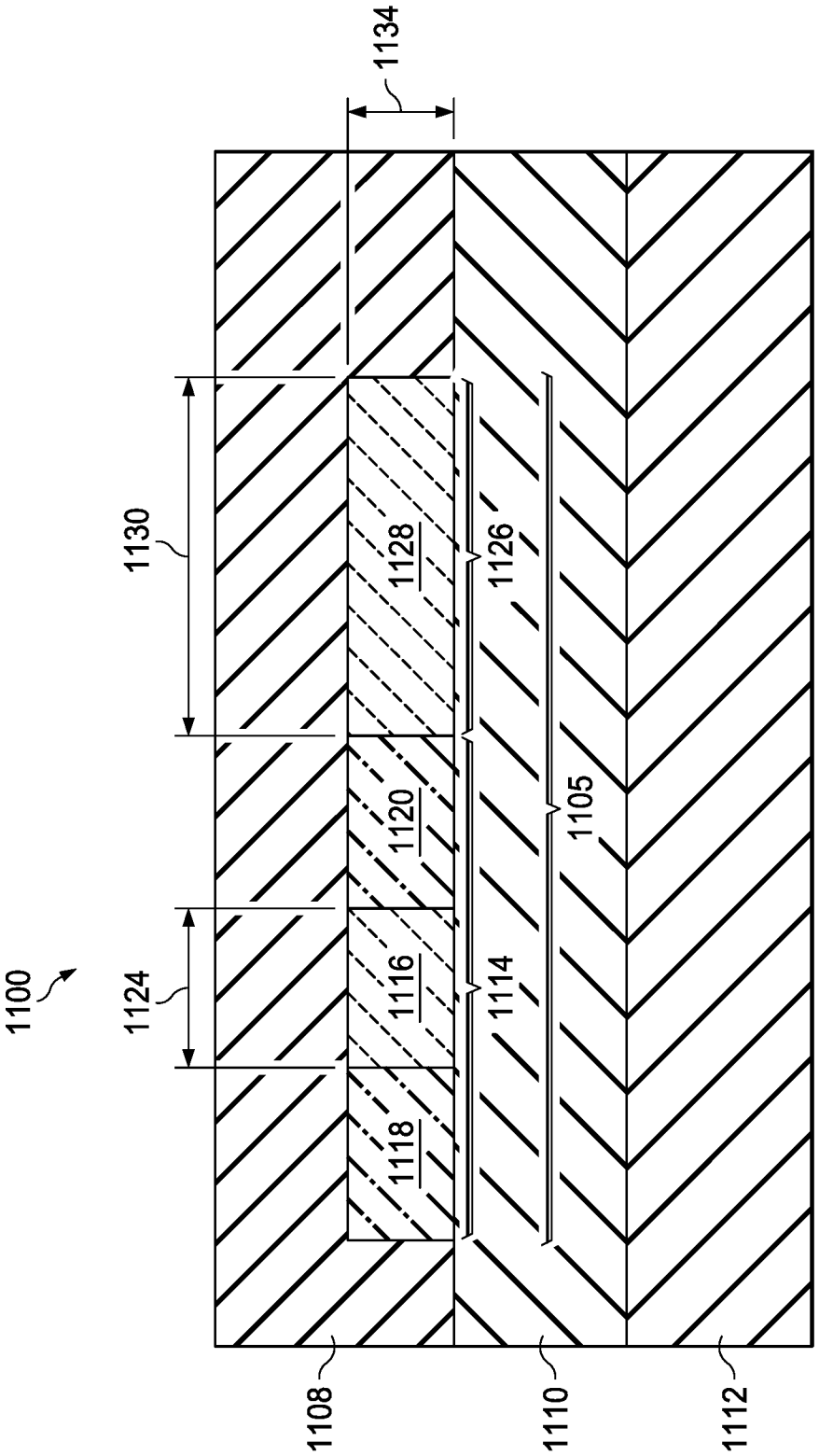

1134
1130
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1126
1120
1105
1124
1116
1114
1100
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1112

FIG. 11

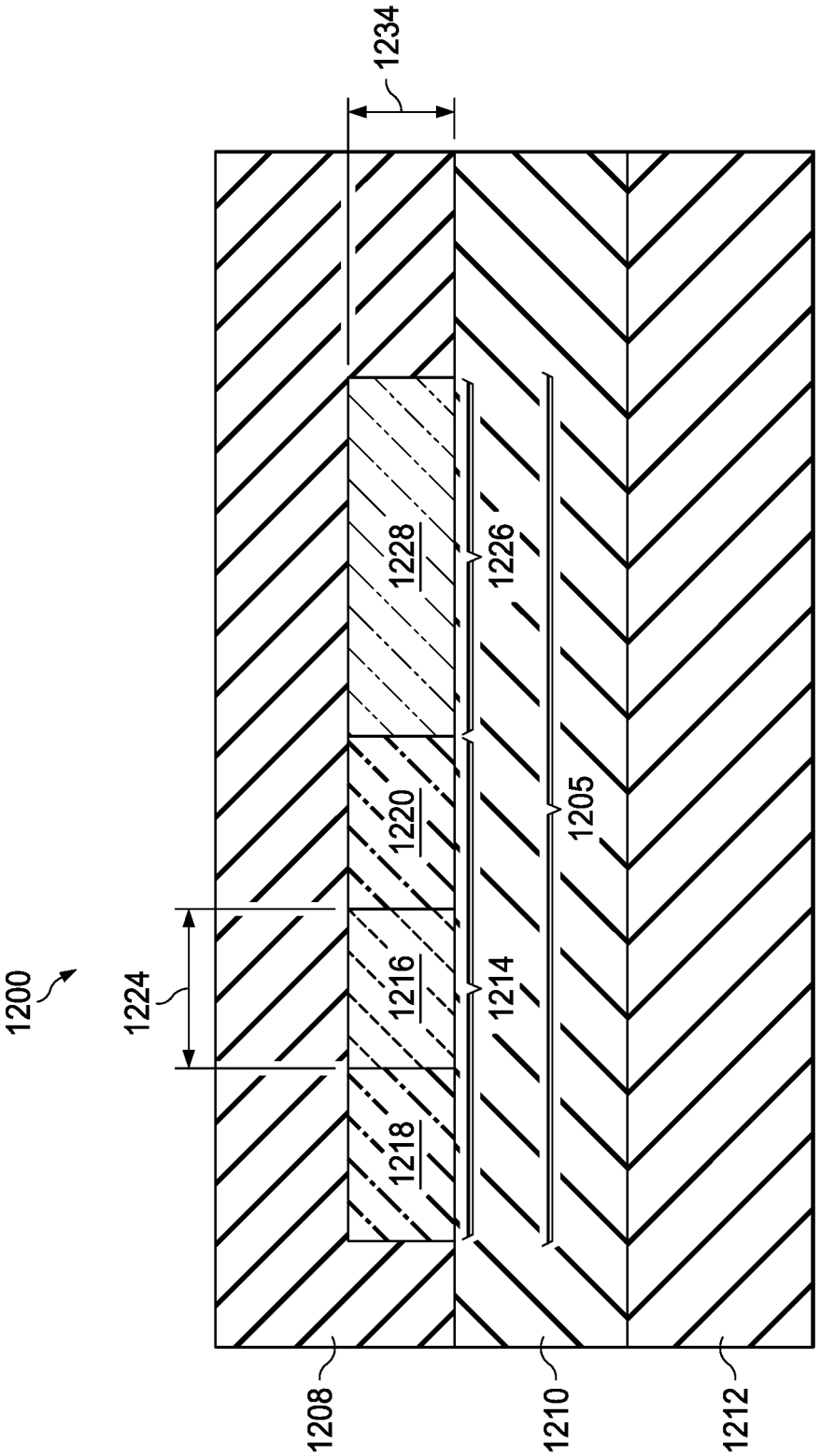

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FIG. 12

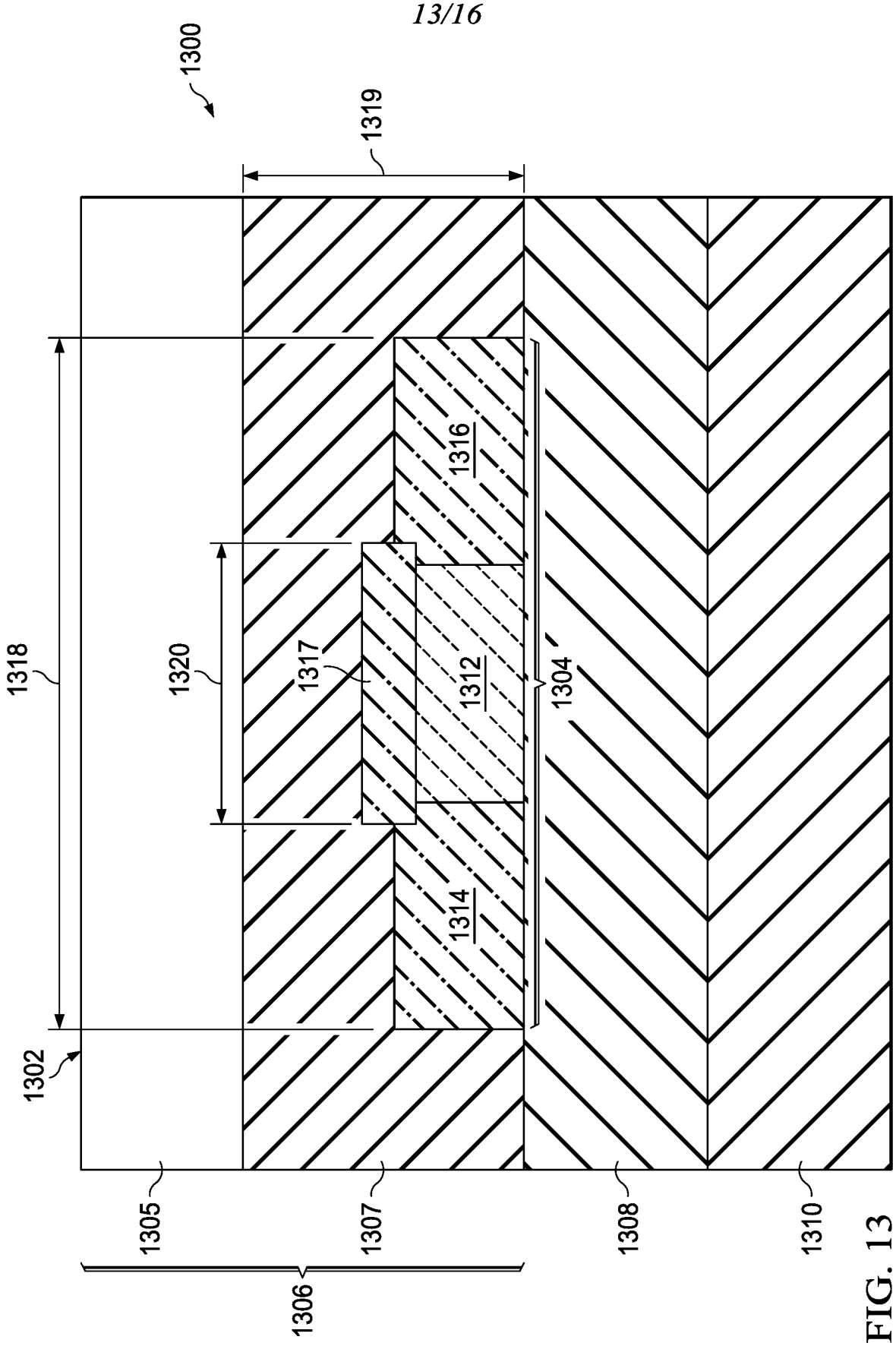

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FIG. 13

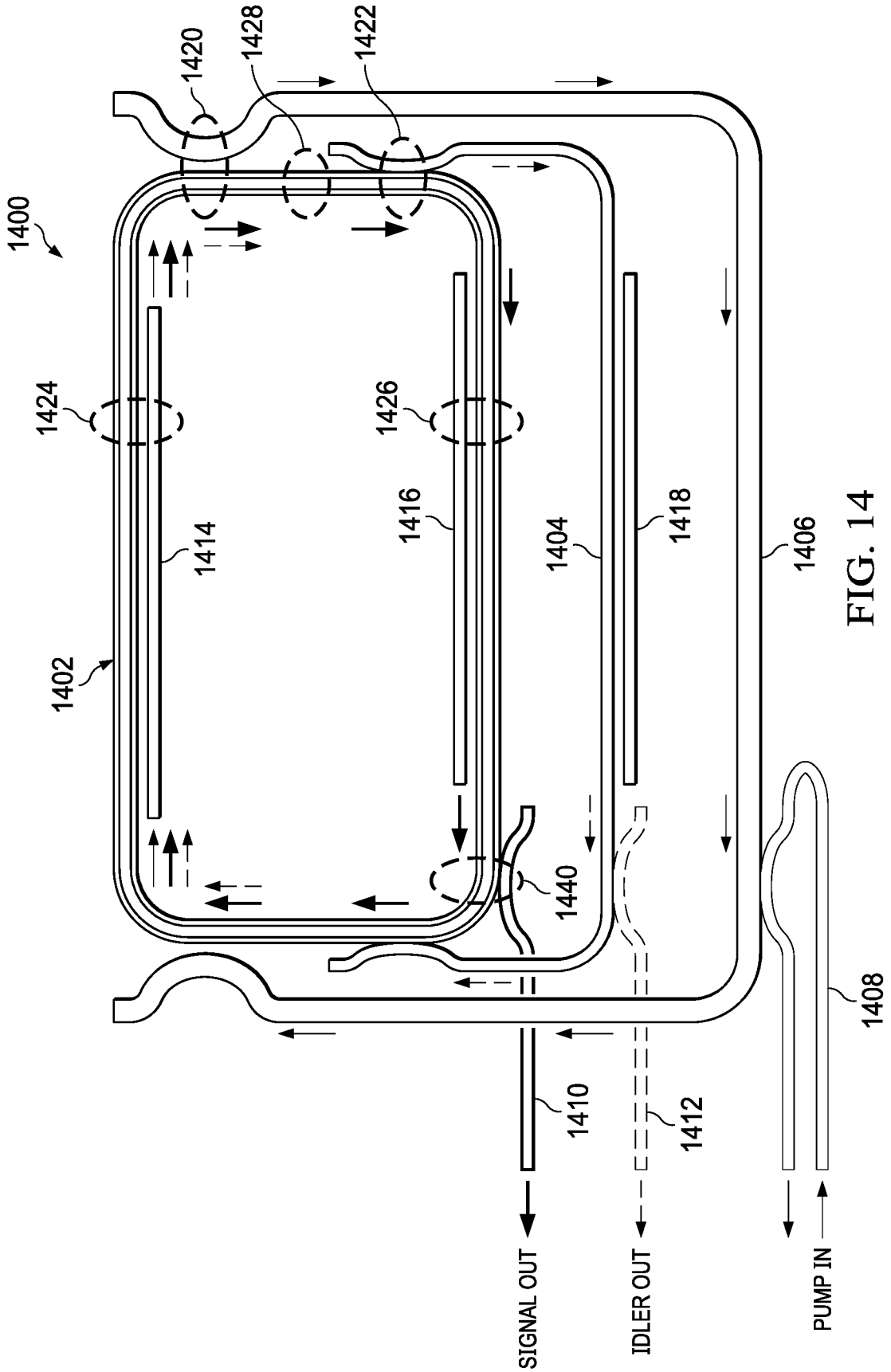

1400
1420
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1404
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1406
1402
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1408
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1412
SIGNAL OUT
IDLER OUT
PUMP IN

FIG. 14

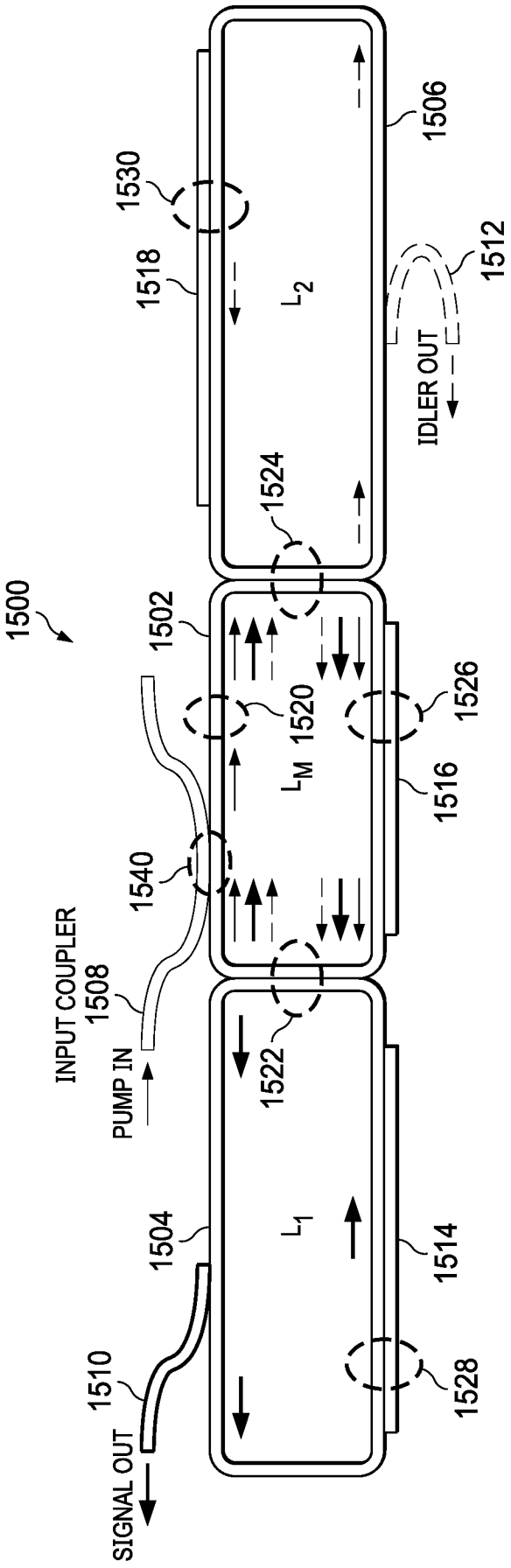

1500
1502
1504
1506
1508
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1512
1514
1516
1518
1520
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1524
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1528
1530
1540
L_1
L_2
L_M
INPUT COUPLER
PUMP IN
IDLER OUT
SIGNAL OUT

FIG. 15

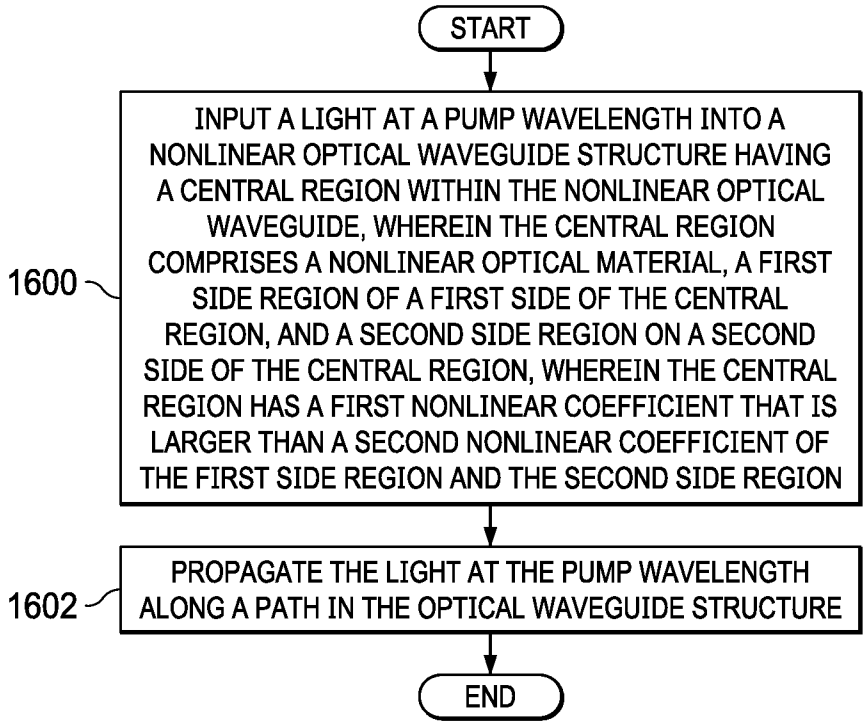

START
INPUT A LIGHT AT A PUMP WAVELENGTH INTO A NONLINEAR OPTICAL WAVEGUIDE STRUCTURE HAVING A CENTRAL REGION WITHIN THE NONLINEAR OPTICAL WAVEGUIDE, WHEREIN THE CENTRAL REGION COMPRISES A NONLINEAR OPTICAL MATERIAL, A FIRST SIDE REGION OF A FIRST SIDE OF THE CENTRAL REGION, AND A SECOND SIDE REGION ON A SECOND SIDE OF THE CENTRAL REGION, WHEREIN THE CENTRAL REGION HAS A FIRST NONLINEAR COEFFICIENT THAT IS LARGER THAN A SECOND NONLINEAR COEFFICIENT OF THE FIRST SIDE REGION AND THE SECOND SIDE REGION
1600
PROPAGATE THE LIGHT AT THE PUMP WAVELENGTH ALONG A PATH IN THE OPTICAL WAVEGUIDE STRUCTURE
1602
END

FIG. 16

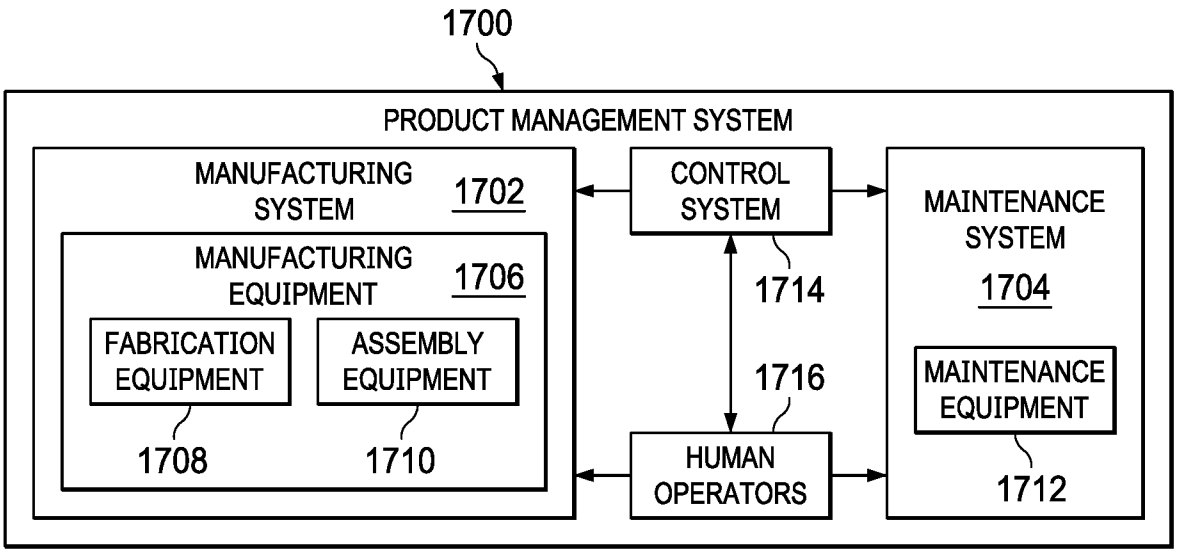

1700
PRODUCT MANAGEMENT SYSTEM
MANUFACTURING SYSTEM
1702
MANUFACTURING EQUIPMENT
1706
FABRICATION EQUIPMENT
ASSEMBLY EQUIPMENT
1708
1710
CONTROL SYSTEM
1714
1716
HUMAN OPERATORS
MAINTENANCE SYSTEM
1704
MAINTENANCE EQUIPMENT
1712

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/071725

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02F1/377 G02F1/35 G02F1/37 G02F1/365 G02B6/293
G02F1/39 G02F1/21 G02B6/12
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)
G02F 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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	US 2005/047702 A1 (PARKER GREG [GB] ET AL) 3 March 2005 (2005-03-03)	1-15, 19-26
Y	paragraphs [0006], [0020], [0027], [0077], [0139], [0168] - [0175], [0199] - [0201] figures 1B, 12, 15-23	16-18
Y	JP 2017 078786 A (NAT INST ADVANCED IND SCIENCE & TECH) 27 April 2017 (2017-04-27) figures 2, 5 paragraph [0020] - paragraph [0025]	16-18

-/--

[x] Further documents are listed in the continuation of Box C.
[x] See patent family annex.

* Special categories of cited documents :

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"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
9 February 2022	28/02/2022

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

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	WO 2019/208582 A1 (SUMITOMO ELECTRIC INDUSTRIES [JP]) 31 October 2019 (2019-10-31) paragraph [0003] & US 2021/026222 A1 (NAGANO SHIGEHIRO [JP]) 28 January 2021 (2021-01-28) paragraph [0004] paragraph [0027] - paragraph [0030]	1-26
A	US 2012/093459 A1 (MATHAI SAGI VARGHESE [US] ET AL) 19 April 2012 (2012-04-19) paragraph [0026]	1-26
A	US 6 078 717 A (NASHIMOTO KEIICHI [JP] ET AL) 20 June 2000 (2000-06-20) figures 1-19	1-26
A	US 6 438 291 B1 (DUCK GARY [CA] ET AL) 20 August 2002 (2002-08-20) figure 3	1-26
A	US 5 002 349 A (CHEUNG KWOK-WAI [US] ET AL) 26 March 1991 (1991-03-26) paragraph [0001]; figures 1-9	1-26
A	US 2020/256722 A1 (NAJAFI FARAZ [US] ET AL) 13 August 2020 (2020-08-13) paragraph [0042]	1-26
10 A	JP H01 134310 A (FUJITSU LTD) 26 May 1989 (1989-05-26) figures 1-5	1-26
10 A	JP H01 134309 A (FUJITSU LTD) 26 May 1989 (1989-05-26) figures 1-3	1-26

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6 483 953 B1 (MCBRIEN GREGORY J [US] ET AL) 19 November 2002 (2002-11-19) figures 4-9	1-26
A	US 2019/361315 A1 (ZHOU JIANYING [US]) 28 November 2019 (2019-11-28) figures 1-24	1-26
A	FEJER M M ET AL: "QUASI-PHASE-MATCHED SECOND HARMONIC GENERATION: TUNING AND TOLERANCES", IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE, USA, vol. 28, no. 11, 1 November 1992 (1992-11-01), pages 2631-2654, XP000309655, ISSN: 0018-9197, DOI: 10.1109/3.161322 abstract	1-26
A	US 5 206 868 A (DEACON DAVID A G [US]) 27 April 1993 (1993-04-27) paragraph [0001]; figures 1-12	1-26
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A	BOSSHARD C: "CASCADING OF SECOND-ORDER NONLINEARITIES IN POLAR MATERIALS", ADVANCED MATERIALS, VCH PUBLISHERS, DE, vol. 8, no. 5, 1 May 1996 (1996-05-01), pages 385-397, XP000587516, ISSN: 0935-9648, DOI: 10.1002/ADMA.19960080503 abstract	1-26
A	US 7 495 823 B2 (NORTHROP GRUMMAN CORP [US]) 24 February 2009 (2009-02-24) paragraph [0029] figure 2	1-26
2 A	JP H05 216079 A (NIPPON TELEGRAPH & TELEPHONE) 27 August 1993 (1993-08-27) figures 1-8	1-26

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1

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/071725

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 295 218 A (AGOSTINELLI JOHN A [US] ET AL) 15 March 1994 (1994-03-15) column 3, line 30 - line 60 figures 1-2 -----	1-26

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2021/071725

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