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

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
27 February 2014 (27.02.2014)

WIPO | PCT

(10) **International Publication Number**
WO 2014/031081 A1

(51) **International Patent Classification**:
G02B 6/35 (2006.01) ***G02B 6/12*** (2006.01) ***G02F 1/035*** (2006.01)

(21) **International Application Number**:
PCT/SG2013/000361

(22) **International Filing Date**:
22 August 2013 (22.08.2013)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
201206312-9 24 August 2012 (24.08.2012) SG

(71) **Applicant**: **AGENCY FOR SCIENCE, TECHNOLOGY AND RESEARCH** [SG/SG]; 1 Fusionopolis Way, #20-10 Connexis, Singapore 138632 (SG).

(72) **Inventors**: **SONG, Junfeng**; c/o Industry Development, Institute of Microelectronics, 11 Science Park Road, Singapore Science Park 2, Singapore 117685 (SG). **LUO, Xianshu**; c/o Industry Development, Institute of Microelectronics, 11 Science Park Road, Singapore Science Park 2, Singapore 117685 (SG). **YU, Mingbin**; c/o Industry Development, Institute of Microelectronics, 11 Science Park Road, Singapore Science Park 2, Singapore 117685 (SG). **LO, Guo Qiang Patrick**; c/o Industry Development, Institute of Microelectronics, 11 Science Park Road, Singapore Science Park 2, Singapore 117685 (SG).

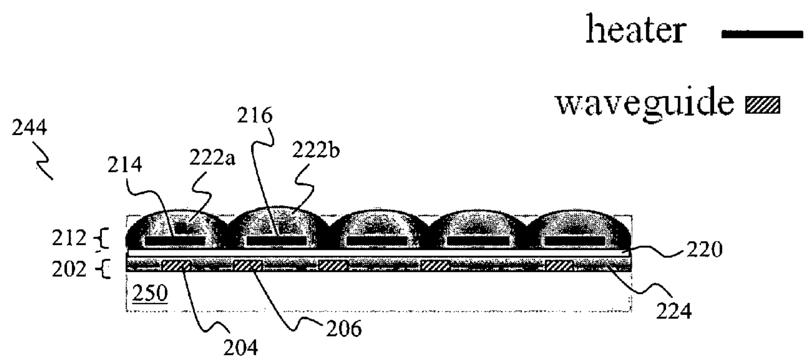
(74) **Agent**: **VIERING, JENTSCHURA & PARTNER LLP**; P.O. Box 1088, Rochor Post Office, Rochor Road, Singapore 911833 (SG).

(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, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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

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

(54) **Title**: WAVEGUIDE STRUCTURE AND OPTICAL STRUCTURE



(57) **Abstract**: According to embodiments of the present invention, a waveguide structure is provided. The waveguide structure includes a support substrate, a waveguide array disposed on the support substrate, a thermal extension layer disposed over the waveguide array, and a thermal heater disposed over the thermal extension layer, wherein the thermal extension layer has a high thermal conductivity sufficient to uniformly distribute the generated heat from the thermal heater to the waveguide array, and wherein the waveguide array, the thermal extension layer and the thermal heater are monolithically integrated on the support substrate. According to further embodiments of the present invention, an optical structure is also provided.

WO 2014/031081 A1

WAVEGUIDE STRUCTURE AND OPTICAL STRUCTURE

Cross-Reference To Related Application

[0001] This application claims the benefit of priority of Singapore patent application No. 201206312-9, filed 24 August 2012, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

[0002] Various embodiments relate to a waveguide structure and an optical structure.

Background

[0003] An optical phase array using on-chip waveguides is very important in various applications, such as optical beam steering, arrayed waveguide grating (AWG), 1 x N or N x N optical switches, optical multiplexer/demultiplexer, etc. In a waveguide phase array, the waveguide length difference is fixed between adjacent waveguides, which promises high optical performances by the constructive and destructive interference at the output end. However, one major problem for such a phase array is the fabrication imperfection induced phase difference, which significantly changes the properties of the destructive/constructive interference, thus the optical device performance.

[0004] In order to solve the above-mentioned problem, various thermally tunable phase arrays have been proposed and demonstrated for dynamic adjusting of the phase difference. However, the heat distributions in nearly all the existing approaches are not uniform, which again induces phase difference.

[0005] Further, conventional devices may include $LiNbO_3$ based devices, may require mechanical control or may include a resister strip array which leads to a non-uniform temperature distribution. Conventional devices (e.g. AWG) may also provide a very large gap between waveguides, with every waveguide having a heater strip, and then tuning every heater one by one, which may lead to a bigger size, and complete operating, which may require many DC power supplies for tuning every waveguide of the plurality of waveguides of the conventional devices, one by one.

[0006] AWG is a key building block for telecommunication and computer communication applications. Current widely used planar lightwave circuit (PLC) AWGs lack the robustness in terms of footprint, fast dynamic tuning and large scale integrating capability, as compared to silicon devices. On the other hand, silicon-on-insulator (SOI)-based AWGs tend to drift from the designed performance due to low fabrication tolerance, and also are easier to be affected by environmental temperatures. Thus, SOI-based AWGs require a dynamic control to satisfy the performance requirements.

[0007] There is therefore need for a high-performance tunable waveguide array.

Summary

[0008] According to an embodiment, a waveguide structure is provided. The waveguide structure may include a support substrate, a waveguide array disposed on the support substrate, a thermal extension layer disposed over the waveguide array, and a thermal heater disposed over the thermal extension layer, wherein the thermal extension layer has a high thermal conductivity sufficient to uniformly distribute the generated heat from the thermal heater to the waveguide array, and wherein the waveguide array, the thermal extension layer and the thermal heater are monolithically integrated on the support substrate.

[0009] According to an embodiment, an optical structure is provided. The optical structure may include a plurality of input waveguides configured to receive an input light, a plurality of output waveguides configured to couple light out of the optical structure, and a waveguide structure as described herein coupled between the plurality of input waveguides and the plurality of output waveguides.

Brief Description of the Drawings

[0010] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0011] FIG. 1A shows a schematic block diagram of a waveguide structure, according to various embodiments.

[0012] FIG. 1B shows a cross-sectional representation of the waveguide structure of the embodiment of FIG. 1A.

[0013] FIG. 1C shows a schematic block diagram of an optical structure, according to various embodiments.

[0014] FIG. 2A shows a top view and a cross-sectional view of a waveguide structure before thermal tuning, while FIG. 2B shows a top view and a cross-sectional view of the waveguide structure after thermal tuning, according to various embodiments.

[0015] FIGS. 2C to 2E respectively show schematic cross-sectional views of waveguide structures.

[0016] FIGS. 3A to 3E respectively show schematic top views of optical structures incorporating the waveguide structure of various embodiments.

[0017] FIG. 4A shows a top view of an optical structure before thermal tuning, while FIG. 4B shows a top view of the optical structure after thermal tuning, according to various embodiments.

[0018] FIG. 5A shows a plot of simulated temperature distribution of a waveguide structure without a thermal extension layer.

[0019] FIG. 5B shows a plot of simulated temperature distribution of a waveguide structure with a thermal extension layer, according to various embodiments.

[0020] FIG. 6 shows a plot of simulated temperature distribution results for aluminium (Al) thermal extension layers of different thicknesses, according to various embodiments.

[0021] FIG. 7 shows a plot of simulated light propagation through a waveguide structure of various embodiments.

[0022] FIGS. 8A to 8L show respective plots of simulated light propagation through a waveguide structure of various embodiments.

Detailed Description

[0023] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0024] Embodiments described in the context of one of the methods or devices are analogously valid for the other method or device. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

[0025] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0026] In the context of various embodiments, the articles "a", "an" and "the" as used with regard to a feature or element includes a reference to one or more of the features or elements.

[0027] In the context of various embodiments, the phrase "at least substantially" may include "exactly" and a reasonable variance.

[0028] In the context of various embodiments, the term "about" as applied to a numeric value encompasses the exact value and a reasonable variance.

[0029] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0030] As used herein, the phrase of the form of "at least one of A or B" may include A or B or both A and B. Correspondingly, the phrase of the form of "at least one of A or B or C", or including further listed items, may include any and all combinations of one or more of the associated listed items.

[0031] Various embodiments may relate to fields including silicon (Si) photonics and on-chip optical interconnect.

[0032] Various embodiments may provide a thermo-optically tunable phase array, for example a thermo-optically tunable phase array with uniform heat distribution.

[0033] Various embodiments may provide a waveguide structure with tunable phase. The waveguide structure may be employed in or as part of an optical structure. Various embodiments may be or may form part of a thermo-optical structure or device. In various embodiments, a thermal extension layer may be incorporated to enable uniform heat distribution, which may lead to improvement in thermal-optical devices. Various embodiments may also include a thermal expansion layer design.

[0034] Various embodiments of the waveguide structure and/or the optical structure may incorporate on-chip components or elements, for example, a waveguide array, a thermal extension layer, and a thermal heater, thereby achieving integration. Various embodiments may incorporate a thermal effect and/or electrical control for operation. Various embodiments may have a compact footprint.

[0035] Various embodiments may provide a waveguide structure having a set of arrayed waveguides with a fixed delay line. A thermal heater may be integrated on the top of the arrayed waveguides for phase tunability, for example of tuning of light propagating through the arrayed waveguides. The thermal heater may be specifically designed in order to keep the tunable phase difference. A thermal extension layer (or thermal distribution layer) may be designed and arranged between the thermal heater and the arrayed waveguides, using a highly thermal conductive material in order to uniformly distribute the heat generated by the thermal heater.

[0036] Various embodiments may also provide an optical structure having multiple input waveguides, multiple output waveguides, two star couplers, and a set of arrayed waveguides with a fixed delay line. One end (e.g. input end) of the set of arrayed waveguides may be coupled to the multiple input waveguides via one of the star couplers while the other end (e.g. output end) of the set of arrayed waveguides may be coupled to the multiple output waveguides via a second star coupler. A thermal heater may be integrated on the top of the arrayed waveguides for phase tunability, for example tuning of light propagating through the arrayed waveguides. The thermal heater may be specifically designed in order to keep the tunable phase difference. A thermal extension layer (or thermal distribution layer) may be designed and arranged between the thermal heater and the arrayed waveguides, using a highly thermal conductive material in order to uniformly distribute the heat generated by the thermal heater. Non-limiting examples of the optical structure of various embodiments may be as shown in FIGS. 3A to 3E.

[0037] Various embodiments may provide a monolithic integrated circuit or structure by involving integration of many components on the same chip which may be fabricated using complementary metal-oxide-semiconductor (CMOS) processes. This may enable the distance of the thermal heater and the thermal extension layer of various embodiments to be controllable and in micro-scale. Also, a monolithic integration system may be provided with precise alignment to the arrayed waveguide grating for heating in any local area or whole area of the waveguide array by design choice or device/circuits requirement. In this way, a portion or a whole area of any one or more or all of the waveguides of the waveguide array may be heated for thermal tuning. Furthermore, by using monolithic integration, assembling of separate chips or pieces may be eliminated, and cost may be reduced (e.g. the assembling cost may be eliminated).

[0038] Various embodiments may enable local heating to the arrayed waveguides for the control of the arrayed waveguides phase change. In various embodiments, only local heating is provided to the arrayed waveguides for the control of only the arrayed waveguides phase change. In contrast, in conventional devices, the entire device (e.g. AWG) assembly is heated up, including the input/output waveguides, the input/output star couplers, and the arrayed waveguides, thus changing the refractive index (phase) of all these components.

[0039] The form and weight factors of the structures of various embodiments may be less as compared to conventional structures. For example, for various embodiments, the size may be determined by the AWG, and not the heater. For conventional devices, the factor determination is more complicated, since typically the external heater that is used is much larger.

[0040] Various embodiments may enable simplification of 1×N and N×N optical switch structures. Various embodiments may also allow realization of tunable arrayed waveguide gratings (AWGs).

[0041] Various embodiments may be employed in various applications, for example for light beam direction control for 1×N and N×N optical switches. Various embodiments may also be employed in or as a tunable AWG. Various embodiments may be applicable in a variety of material platforms or technologies, including but not limited to silicon-on-insulator (SOI), planar lightwave circuit (PLC), III-V materials, among others.

[0042] As a non-limiting example of application in an optical waveguide array, e.g. in an optical switch, based on Fraunhofer diffraction, light may be inputted or provided from one of the waveguides and which may separate into multi-waveguides with a fixed length difference. Interference may then occur and the multiple lights may interfere in or at the output facet with a fixed output light direction which may be determined by the phase difference. In various embodiments, the control of the phase difference among the multiple waveguides may control the output light properties. The phase difference may be controlled by thermo-optical effect.

[0043] FIG. 1A shows a schematic block diagram of a waveguide structure 100, while FIG. 1B shows a cross-sectional representation of the waveguide structure 100, according to various embodiments. The waveguide structure 100 includes a support substrate 102, a waveguide array 104 disposed on the support substrate 102, a thermal extension layer 106 disposed over the waveguide array 104, and a thermal heater 108 disposed over the thermal extension layer 106, wherein the thermal extension layer 106 has a high thermal conductivity sufficient to uniformly distribute the generated heat from the thermal heater 108 to the waveguide array 104, and wherein the waveguide array 104, the thermal extension layer 106 and the thermal heater 108 are monolithically integrated on the support substrate 102. The line represented as 110 is illustrated to show the relationship between the support substrate 102, the waveguide array 104, the thermal extension layer 106 and the thermal heater 108, which may include at least one of electrical coupling, mechanical coupling or thermal coupling.

[0044] In other words, the waveguide structure 100 may include a carrier or a support substrate 102 where a waveguide array 104 may be monolithically integrated on the support substrate 102. The waveguide array 104 may be used for propagation of light, where a light may be coupled into and propagate through the waveguide array 104 and subsequently exit from the waveguide array 104. The waveguide structure 100 may further include a thermal heater 108 which may be monolithically integrated on the support substrate 102. The waveguide structure 100 may further include a thermal extension layer 106 which may be monolithically integrated on the support substrate 102, where the thermal extension layer 106 may be arranged in between the waveguide array 104 and the thermal heater 108. The thermal extension layer 106 may be arranged over the waveguide array 104 or a portion thereof, and a thermal heater 108 may be arranged over the thermal extension layer 106. In this way, heat or a portion thereof generated by the thermal heater 108 may be received by the thermal extension layer 106 which may then distribute the received heat to or onto the waveguide array 104. The heat distributed onto the waveguide array 104 may allow tuning of light propagating in the waveguide array 104. For example, the heat received by the waveguide array 104 may change a property (e.g. optical property; refractive index) of the waveguide array 104, which in turn may affect propagation of light propagating within the waveguide array 104. Hence, the waveguide array 104 may be thermo-optically tunable.

[0045] The thermal extension layer 106 may have a thermal conductivity that may be sufficient to at least substantially uniformly distribute the generated heat from the thermal heater 108 to the waveguide array 104. This may mean that, by means of the thermal extension layer 106, the heat distribution or temperature distribution on the waveguide array 104 may be at least substantially uniform. In the context of various embodiments, therefore, the thermal extension layer 106 may be a thermal distribution layer.

[0046] In various embodiments, the waveguide structure 100 may allow local heating of the waveguide array 104, for controlling or tuning the refractive index (phase) of the waveguide array 104. This may change the phase of the light propagating through the waveguide array 104.

[0047] In the context of various embodiments, the term “monolithically integrated” may mean that the waveguide array 104, the thermal extension layer 106 and the thermal heater 108 may be integrally formed on the support substrate 102, in contrast to discrete components being assembled to form a waveguide structure. In addition, the waveguide array 104, the thermal extension layer 106 and the thermal heater 108 being monolithically integrated on the support substrate 102 may mean that the waveguide array 104, the thermal extension layer 106 and the thermal heater 108 are on-chip components, in contrast to external components. Therefore, a monolithic integrated waveguide structure 100 may be formed, involving integration of the waveguide array 104, the thermal extension layer 106 and the thermal heater 108 on the same chip. In this way, the manufacturability of the waveguide structure 100 may be improved and simplified. The waveguide array 104, the thermal extension layer 106 and the thermal heater 108 may be monolithically integrally formed on the support substrate 102 using complementary metal-oxide-semiconductor (CMOS) processes. This may enable the distance between the thermal heater 108 and the thermal extension layer 106 to be controllable and in micro-scale. Further, by monolithically integrating the waveguide array 104, the thermal extension layer 106 and the thermal heater 108 on the support substrate 102, the performance of the waveguide structure 100 may be improved, for example having a lower heat coupling loss, lower optical coupling loss, etc.

[0048] In the context of various embodiments, the waveguide array 104 may have a fixed delay line. This may mean that light or light of each wavelength propagating through the waveguide array 104 may undergo a constant change of phase.

[0049] In the context of various embodiments, the thermal extension layer 106 may also be known as a heat extension layer or a heater extension layer.

[0050] In various embodiments, the thermal extension layer 106 may be a planar layer.

[0051] In various embodiments, the thermal extension layer 106 may have a shape or form that may correspond to the shape of the thermal heater 108. In various embodiments, the thermal extension layer 106 may at least substantially overlap with the thermal heater 108.

[0052] In the context of various embodiments, the thermal extension layer 106 may have a thermal conductivity at least substantially equal to or more than about 100 W/mK (e.g. ≥ 100 W/mK). For example, the thermal extension layer 106 may have a thermal conductivity in a range of between about 100 W/mK and about 1000 W/mK, e.g. between about 100 W/mK and about 500 W/mK, between about 100 W/mK and about 200 W/mK, between about 300 W/mK and about 1000 W/mK, between about 500 W/mK and about

1000 W/mK, or between about 200 W/mK and about 600 W/mK. However, it should be appreciated that other values for the thermal conductivity of the thermal extension layer 106 may be possible, for example a thermal conductivity of more than 1000 W/mK.

[0053] In various embodiments, the higher the thermal conductivity of the thermal extension layer 106, the faster the tuning speed of the waveguide structure 100 may be.

[0054] In the context of various embodiments, the support substrate 102 may be a silicon (Si)-based substrate, for example a silicon substrate/wafer, or a silicon-on-insulator (SOI).

[0055] In the context of various embodiments, the thermal heater 108 may be a heater strip.

[0056] In the context of various embodiments, the thermal heater 108 may be a single structure, for example one heater element.

[0057] In the context of various embodiments, the thermal heater 108 may have a continuous structure.

[0058] In the context of various embodiments, the thermal heater 108 may be arranged in a meander or serpentine shape or pattern.

[0059] In the context of various embodiments, the thermal heater 108 may include or may be made of a thermal conductive material, e.g. a metal. The thermal heater 108 may include a material including but not limited to titanium (Ti), titanium nitride (TiN), tantalum nitride (TaN) or doped silicon (Si).

[0060] In various embodiments, the waveguide array 104 may include a plurality of waveguides (for example, two, three, four, five or any higher number of waveguides). The plurality of waveguides may extend substantially parallel and spaced apart from each other. The plurality of waveguides may be arranged along a same plane. The plurality of waveguides may be arranged side by side.

[0061] In various embodiments, each of the plurality of waveguides may be spaced apart from another of the plurality of waveguides at a fixed or equal interval. This may mean that the respective spacings between successive adjacent waveguides may be at least substantially same.

[0062] In various embodiments, each of the plurality of waveguides may be spaced apart from another of the plurality of waveguides at a varying or unequal interval. This may mean that the respective spacings between successive adjacent waveguides may be different.

[0063] In various embodiments, the thermal heater 108 may include a plurality of heater elements (for example, two, three, four, five or any higher number of heater elements). The plurality of heater elements may extend substantially parallel and spaced apart from each other. The plurality of heater elements may be arranged along a same plane. The plurality of heater elements may be arranged side by side. In various embodiments, at least one heater element of the plurality of heater elements may be a heater strip. In various embodiments, the plurality of heater elements may be electrically coupled together, for example via one or more common electrodes.

[0064] In various embodiments, each of the plurality of heater elements may be spaced apart from another of the plurality of heater elements at a fixed or equal interval. This may mean that the respective spacings between successive adjacent heater elements may be at least substantially same.

[0065] In various embodiments, each of the plurality of heater elements may be spaced apart from another of the plurality of heater elements at a varying or unequal interval. This may mean that the respective spacings between successive adjacent heater elements may be different.

[0066] In various embodiments, the thermal extension layer 106 may have a shape or form that may correspond to the shape or configuration of the arrangement of the plurality of heater elements. In various embodiments, the thermal extension layer 106 may at least substantially overlap with the plurality of heater elements.

[0067] In various embodiments, the waveguide array 104 may include a plurality of waveguides, and the thermal heater 108 may include a plurality of heater elements. In various embodiments, the number of the plurality of waveguides may be the same as the number of the plurality of heater elements or may be different. In various embodiments, a heater element may be associated with a respective waveguide.

[0068] In various embodiments, the thermal heater 108 may include a plurality of heater elements extending substantially parallel and spaced apart from each other at a fixed interval, and wherein the waveguide array 104 may include a plurality of waveguides extending substantially parallel and spaced apart from each other at a varying interval.

This may mean that there may be an offset between a respective heater element and a particular waveguide associated with the respective heater element.

[0069] In the context of various embodiments, the thermal extension layer 106 may have a thickness in a range of about 100 nm to about several microns (micrometers), for example between about 100 nm and about 10 μm, between about 100 nm and about 5 μm, between about 100 nm and about 1 μm, between about 1 μm and about 10 μm, between about 1 μm and about 5 μm, between about 5 μm and about 10 μm, or between about 500 nm and about 5 μm, e.g. about 100 nm, about 200 nm or about 250 nm. Nevertheless, it should be appreciated that other thicknesses may be provided. In various embodiments, the thicker the thermal extension layer 106, the more uniform the heat distribution resulting from the thermal extension layer 106. However, a thicker thermal extension layer 106 may lower the tuning speed.

[0070] In the context of various embodiments, the thermal extension layer 106 may include or may be made of a thermal conductive material, e.g. a metal. The thermal extension layer 106 may include a material including but not limited to aluminium (Al), copper (Cu), or silicon (Si). However, it should be appreciated that other materials with a relatively high thermal conductivity may be used for the thermal extension layer 106 for thermal or heat distribution.

[0071] In the context of various embodiments, an insulating layer or a passivation layer may be provided over the waveguide array 104, the thermal extension layer 106 and the thermal heater 108. In various embodiments, the waveguide array 104, the thermal extension layer 106 and the thermal heater 108 may be embedded within the passivation layer.

[0072] While FIG. 1B shows that adjacent components may be in direct contact, it should be appreciated that the waveguide array 104 may be arranged spaced apart from the support substrate 102, and/or the thermal extension layer 106 may be arranged spaced apart from the waveguide array 104, and/or the thermal heater 108 may be arranged spaced apart from the thermal extension layer 106.

[0073] FIG. 1C shows a schematic block diagram of an optical structure 150, according to various embodiments. The optical structure 150 includes a plurality of input waveguides 152 configured to receive an input light, a plurality of output waveguides 154 configured to couple light out of the optical structure 150, and a waveguide structure 156 coupled between the plurality of input waveguides 152 and the plurality of output waveguides 154. The waveguide structure 156 may be similar to the embodiments as described in the context of the waveguide structure 100 of FIGS. 1A and 1B. In FIG. 1C, the line represented as 158 is illustrated to show the relationship between the plurality of input waveguides 152, the plurality of output waveguides 154 and the waveguide structure 156, which may include at least one of optical coupling or mechanical coupling.

[0074] In other words, the optical structure 150 may include a plurality of input waveguides 152, a plurality of output waveguides 154, and a waveguide structure 156 arranged therebetween, which may be optically coupled to each other. An input light may be received by the plurality of input waveguides 152, which may propagate through the plurality of input waveguides 152 and subsequently optically coupled into the waveguide structure 156. The light received by the waveguide structure 156 may be tuned (e.g. thermo-optically tuned) within the waveguide structure 156. Thereafter, the light from the waveguide structure 156 may be coupled to the plurality of output waveguides 154, which may subsequently exit the optical structure 150 as an output light.

[0075] In various embodiments, the waveguide structure 156 may be configured to be thermally controlled to compensate for a phase error between the input light and the light out of the optical structure 150.

[0076] In various embodiments, the optical structure 150 may further include a first coupler (e.g. a first optical coupler) arranged between the plurality of input waveguides 152 and an input end of the waveguide structure 156, and a second coupler (e.g. a second optical coupler) arranged between an output end of the waveguide structure 156 and the plurality of output waveguides 154. In this way, light may be coupled from the plurality of input waveguides 152 into the waveguide structure 156 by means of the first coupler, and light may be coupled from the waveguide structure 156 into the plurality of output waveguides 154 by means of the second coupler.

[0077] In various embodiments, at least one of the first coupler or the second coupler may be a star coupler.

[0078] Schematics of applications of various embodiments in a tunable phase array are illustrated in FIGS. 2A and 2B.

[0079] FIG. 2A shows a top view and a cross-sectional view (taken along line A-A') of a waveguide structure 200 before thermal tuning, while FIG. 2B shows a top view and a cross-sectional view (taken along line B-B') of the waveguide structure 200 after thermal tuning. The waveguide structure 200 may be a thermally tunable phase array with a uniform heating distribution.

[0080] The waveguide structure 200 includes a waveguide array 202 monolithically integrated on a support substrate (not shown). The waveguide array 202 may include a plurality of waveguides. As an example as shown in FIGS. 2A and 2B, the waveguide array 202 may include six optical waveguides, for example as represented by 204 for a first waveguide and 206 for a second waveguide. The waveguide structure 200 may further include a thermal heater 212 monolithically integrated on the support substrate (not shown). The thermal heater 212 may be arranged over a portion of the waveguide array 202. The thermal heater 212 may include an array or plurality of heater elements. As an example as shown in FIGS. 2A and 2B, the thermal heater 212 may include five heater elements, for example as represented by 214 for a first heater element and 216 for a second heater element.

[0081] The plurality of waveguides, e.g. 204, 206, may be arranged at least substantially parallel to each other. The plurality of waveguides, e.g. 204, 206, may be arranged spaced apart from each other by a spacing. The plurality of waveguides, e.g. 204, 206, may be arranged with a non-uniform or un-equal spacing between adjacent waveguides.

[0082] The plurality of heater elements, e.g. 214, 216, may be arranged at least substantially parallel to each other. The plurality of heater elements, e.g. 214, 216, may be arranged spaced apart from each other by a spacing. The plurality of heater elements, e.g. 214, 216, may be arranged with a uniform or equal spacing between adjacent heater elements. The plurality of heater elements, e.g. 214, 216, may have different sizes, e.g. different lengths.

[0083] In various embodiments, in addition to the parallel heater elements, e.g. 214, 216, a heat extension layer or thermal extension layer 220 may be designed and arranged between the plurality of heater elements, e.g. 214, 216, and the plurality of waveguides, e.g. 204, 206, such that the thermal extension layer 220 may be disposed over the waveguide array 202, and the thermal heater 212 may be disposed over the thermal extension layer 220. The thermal extension layer 220 may be monolithically integrated on the support substrate (not shown). The thermal extension layer 220 may be arranged over at least the portion of the waveguide array 202 corresponding to the thermal heater 212.

[0084] FIG. 2A shows the waveguide structure 200 before thermal tuning or before application of heat to the waveguide array 202 to illustrate the phase change of light propagating in the waveguide array 202. The solid line 230 represents the input phase plane, while the solid line 232 represents the output phase plane. As a result of, for example, fabrication imperfection, a phase difference may be induced between the output phase plane 232 and the input phase plane 230, and therefore the relationship between the output phase plane 232 and the input phase plane 230, as well as the phase between the respective lights propagating through the different waveguides, e.g. 204, 206, may deviate from a fixed delay intended or initially introduced for the waveguide array 202.

[0085] FIG. 2B shows the waveguide structure 200 after thermal tuning or afterapplication of heat to the waveguide array 202 to illustrate the phase change of light propagating in the waveguide array 202. As shown in the cross-sectional view of the waveguide structure 200 of FIG. 2B, the thermal extension layer 220 may be arranged between the thermal heater 212 and the waveguide array 202. The thermal heater 212 including the plurality of heater elements, e.g. 214, 216, may generate heat, for example as represented by 222 for heat generated by the first heater element 214, which may first be radiated towards and onto the thermal extension layer 220. The thermal extension layer 220 may have a high thermal conductivity sufficient to uniformly distribute the heat generated from the thermal heater 212 to the waveguide array 202. This may mean that the heat from the thermal extension layer 220 may become at least substantially uniformly distributed and then flow onto the waveguide array 202, such that the waveguide array 202 may receive at least substantially uniform heat distribution, as represented by 224.

[0086] As shown in the top view of the waveguide structure 200 of FIG. 2B, as a result of the thermal tuning, the output phase plane 232, which may have deviated as a result of additional induced phase difference, may be shifted back to a plane, for example as represented by the dashed line 234, which may be the expected (or intended) output phase plane in operations without the additional induced phase difference. The double-headed arrow represented as 236 illustrates the phase shift as a result of thermal effect. Therefore, in various embodiments, the heat generated by the thermal heater 212 and subsequently at least substantially uniformly distributed by the thermal extension layer 220 onto the waveguide array 202 may compensate for deviation caused by additional induced phase difference. In this way, phase change upon thermal tuning may be at least substantially uniform.

[0087] FIGS. 2C to 2E respectively show schematic cross-sectional views of waveguide structures, illustrating different thermal heater designs for comparison of temperature distributions in the respective waveguide arrays.

[0088] FIG. 2C shows a schematic cross-sectional view of a waveguide structure 240. The waveguide structure 240 includes a waveguide array 202 including a plurality of waveguides, for example including a first waveguide 204, a second waveguide 206 and so on, which are spaced apart unequally between adjacent waveguides. The waveguide structure 240 further includes a thermal heater 212 arranged over the waveguide array 202. The thermal heater 212 includes a plurality of heater elements, for example including a first heater element 214, a second heater element 216 and so on, which are spaced apart equally between adjacent heater elements. The waveguide array 202 and the thermal heater 212 may be embedded within a passivation layer or an insulating layer 250.

[0089] As a non-limiting example, the first heater element 214 may generate and radiate heat, as represented by 222a onto the first waveguide 204, while the second heater element 216 may generate and radiate heat, as represented by 222b onto the second waveguide 206. As illustrated in FIG. 2C, the respective heat distributions received by the first waveguide 204 and the second waveguide 206 may be non-uniform, leading to non-uniform temperature distribution onto the waveguide array 202, which may lead to non-uniform thermal tuning.

[0090] FIG. 2D shows a schematic cross-sectional view of a waveguide structure 242. The waveguide structure 242 includes a waveguide array 202 including a plurality of waveguides, for example including a first waveguide 204, a second waveguide 206, a third waveguide 208 and so on, which are spaced apart unequally between adjacent waveguides. The waveguide structure 242 further includes a thermal heater 212 arranged over the waveguide array 202. The thermal heater 212 includes a plurality of heater elements, for example a first heater element 214, a second heater element 216, a third heater element 218 and so on, which are spaced apart unequally between adjacent heater elements. The waveguide array 202 and the thermal heater 212 may be embedded within a passivation layer 250.

[0091] As a non-limiting example, the first heater element 214 may generate and radiate heat, as represented by 222a onto the first waveguide 204, while the third heater element 218 may generate and radiate heat, as represented by 222c onto the third waveguide 208. As illustrated in FIG. 2D, the respective heat distributions received by the first waveguide 204 and the third waveguide 208 may be non-uniform, leading to non-uniform temperature distribution onto the waveguide array 202, which may lead to non-uniform thermal tuning.

[0092] FIG. 2E shows a schematic cross-sectional view of a waveguide structure 244. The waveguide structure 244 includes a waveguide array 202 including a plurality of waveguides, for example including a first waveguide 204, a second waveguide 206 and so on, which are spaced apart unequally between adjacent waveguides. The waveguide structure 242 further includes a thermal heater 212 arranged over the waveguide array 202. The thermal heater 212 includes a plurality of heater elements, for example a first heater element 214, a second heater element 216 and so on, which are spaced apart equally between adjacent heater elements. The waveguide structure 242 further includes a thermal extension layer 220 between the waveguide array 202 and the thermal heater 212. The waveguide array 202, the thermal heater 212 and the thermal extension layer 220 may be embedded within a passivation layer 250.

[0093] As a non-limiting example, the first heater element 214 may generate and radiate heat, as represented by 222a onto the thermal extension layer 220, while the second heater element 216 may generate and radiate heat, as represented by 222b onto the thermal extension layer 220. The thermal extension layer 220 may distribute the heat received at least substantially uniformly onto the waveguide array 202. As illustrated in FIG. 2E, the respective heat distributions received by the first waveguide 204 and the second waveguide 206 may be at least substantially uniform, leading to at least substantially uniform temperature distribution, as represented by 224, onto the waveguide array 202, which may lead to at least substantially uniform thermal tuning.

[0094] As shown in FIGS. 2C and 2D, the temperature distributions on the waveguide array 202 may be non-uniform for the respective waveguide structures 240, 242 without a thermal extension layer. In contrast, as illustrated in FIG. 2E, with a thermal extension layer 220 between the thermal heater 212 and the waveguide array 202, the temperature may be distributed at least substantially uniformly in the waveguide layer or the arrayed optical waveguides, e.g. 204, 206.

[0095] Optical structures incorporating the waveguide structure of various embodiments will now be described by way of the following non-limiting examples, with reference to FIGS. 3A to 3E.

[0096] FIG. 3A shows a schematic top view of an optical structure 300, in the form of a 1×N optical switch, incorporating a waveguide structure 302, according to various embodiments. The waveguide structure 302 may be coupled between a plurality of input waveguides 304 and a plurality of output waveguides 306. The optical structure 300 may receive an input signal and provide N output signals.

[0097] The waveguide structure 302 may include a waveguide array 310, a thermal extension layer 312 disposed over the waveguide array 310 or a portion thereof, and a thermal heater 314 disposed over the thermal extension layer 312. The waveguide array 310, the thermal extension layer 312 and the thermal heater 314 may be monolithically integrated on a support substrate (not shown). The waveguide array 310 may include a plurality of waveguides with a pre-determined phase relationship defined for light propagating through the plurality of waveguides. The plurality of waveguides may be arranged at least substantially parallel relative to each other. The plurality of waveguides may be arranged spaced apart from each other. The thermal heater 314 may be or may include a heater element. The thermal heater 314 may be arranged in a meander pattern, overlapping with the thermal extension layer 312 and the waveguide array 310. The thermal heater 314 may be arranged in a trapezoidal shape. The thermal extension layer 312 may have a trapezoidal shape.

[0098] The waveguide array 310 may be coupled (e.g. mechanically and/or optically coupled) to the plurality of input waveguides 304 and the plurality of output waveguides 306 such that light may propagate through the plurality of input waveguides 304, the waveguide array 310 and the plurality of output waveguides 306. In various embodiments, the plurality of input waveguides 304, the waveguide array 310 and the plurality of output waveguides 306 may be a continuous waveguide structure. The plurality of output waveguides 306 may subsequently be coupled to optical channels or optical devices or further waveguides, by means of a coupler 308.

[0099] The optical structure 300 may further include a first conductive interconnect 316a and a second conductive interconnect 316b coupled to the thermal heater 314 for the supply of an electrical signal to the thermal heater 314 to operate the thermal heater 314 to generate heat for thermal tuning of the waveguide structure 302.

[0100] FIG. 3B shows a schematic top view, in a partial expanded view, of an optical structure 320, in the form of a 1×N optical switch, incorporating a waveguide structure 302, according to various embodiments. The waveguide structure 302 may be coupled between a plurality of input waveguides 304 and a plurality of output waveguides 306. The optical structure 320 may be as described in the context of the embodiment of the optical structure 300 of FIG. 3A.

[0101] FIG. 3C shows a schematic top view of an optical structure 330, in the form of a N×N optical switch, incorporating a waveguide structure 302, according to various embodiments. The waveguide structure 302 may be coupled between a plurality of input waveguides 304 and a plurality of output waveguides 306. The optical structure 330 may receive N input signals and provide N output signals.

[0102] The waveguide structure 302 may include a waveguide array 310, a thermal extension layer 312 disposed over the waveguide array 310 or a portion thereof, and a thermal heater 314 disposed over the thermal extension layer 312. The waveguide array 310, the thermal extension layer 312 and the thermal heater 314 may be monolithically integrated on a support substrate (not shown). The waveguide array 310 may include a plurality of waveguides with a pre-determined phase relationship defined for light propagating through the plurality of waveguides. The plurality of waveguides may be arranged at least substantially parallel relative to each other. The plurality of waveguides may be arranged spaced apart from each other. The thermal heater 314 may include a plurality of heater elements overlapping with the thermal extension layer 312 and the waveguide array 310. The plurality of heater elements may be arranged at least substantially parallel relative to each other. The plurality of heater elements may be arranged spaced apart from each other. The plurality of heater elements may have different lengths such that the thermal heater 314 may be arranged in a trapezoidal shape. The thermal extension layer 312 may have a trapezoidal shape.

[0103] The waveguide array 310 may be coupled (e.g. mechanically and/or optically coupled) to the plurality of input waveguides 304 and the plurality of output waveguides 306 such that light may propagate through the plurality of input waveguides 304, the waveguide array 310 and the plurality of output waveguides 306. In various embodiments, the plurality of input waveguides 304 may be coupled to the waveguide array 310 via a first coupler (e.g. star coupler) 332, while the plurality of output waveguides 306 may be coupled to the waveguide array 310 via a second coupler (e.g. star coupler) 334.

[0104] The optical structure 330 may further include a first conductive interconnect 316a and a second conductive interconnect 316b coupled to the thermal heater 314 for the supply of an electrical signal to the thermal heater 314 to operate the thermal heater 314 to generate heat for thermal tuning of the waveguide structure 302.

[0105] FIG. 3D shows a schematic top view of an optical structure 350, in the form of a tunable arrayed waveguide grating (AWG), incorporating a waveguide structure 302, according to various embodiments. The waveguide structure 302 may be coupled between a plurality of input waveguides 304 and a plurality of output waveguides 306. The optical structure 350 may receive a plurality of input signals and provide a plurality of output signals.

[0106] The waveguide structure 302 may include a waveguide array 310, a thermal extension layer 312 disposed over the waveguide array 310 or a portion thereof, and a thermal heater 314 disposed over the thermal extension layer 312. The waveguide array 310, the thermal extension layer 312 and the thermal heater 314 may be monolithically integrated on a support substrate (not shown). The waveguide array 310 may include a plurality of waveguides with a pre-determined phase relationship defined for light propagating through the plurality of waveguides. The plurality of waveguides may be arranged at least substantially parallel relative to each other. The plurality of waveguides may be arranged spaced apart from each other. The thermal heater 314 may include a plurality of heater elements overlapping with the thermal extension layer 312 and the waveguide array 310. The plurality of heater elements may be arranged at least substantially parallel relative to each other. The plurality of heater elements may be arranged spaced apart from each other. The plurality of heater elements may have different lengths such that the thermal heater 314 may be arranged in a trapezoidal shape. The thermal extension layer 312 may have a trapezoidal shape.

[0107] The waveguide array 310 may be coupled (e.g. mechanically and/or optically coupled) to the plurality of input waveguides 304 and the plurality of output waveguides 306 such that light may propagate through the plurality of input waveguides 304, the waveguide array 310 and the plurality of output waveguides 306. In various embodiments, the plurality of input waveguides 304 may be coupled to the waveguide array 310 via a first coupler (e.g. star coupler) 352, while the plurality of output waveguides 306 may be coupled to the waveguide array 310 via a second coupler (e.g. star coupler) 354.

[0108] The optical structure 350 may further include a first conductive interconnect 316a and a second conductive interconnect 316b coupled to the thermal heater 314 for the supply of an electrical signal to the thermal heater 314 to operate the thermal heater 314 to generate heat for thermal tuning of the waveguide structure 302.

[0109] FIG. 3E shows a schematic top view of an optical structure 360, in the form of a tunable arrayed waveguide grating (AWG), incorporating a waveguide structure 302, according to various embodiments. The waveguide structure 302 may be coupled between a plurality of input waveguides 304 and a plurality of output waveguides 306. The optical structure 360 may receive a plurality of input signals and provide a plurality of output signals.

[0110] The waveguide structure 302 may include a waveguide array 310, a first thermal extension layer 312a disposed over a first portion of the waveguide array 310, a first thermal heater 314a disposed over the first thermal extension layer 312a, a second thermal extension layer 312b disposed over a second portion of the waveguide array 310, and a second thermal heater 314b disposed over the second thermal extension layer 312b. The waveguide array 310, the first thermal extension layer 312a, the first thermal heater 314a, the second thermal extension layer 312b and the second thermal heater 314b may be monolithically integrated on a support substrate (not shown).

[0111] The first portion and the second portion of the waveguide array 310 may be adjacent to each other, in close proximity or spaced apart by a pre-determined distance. The first thermal extension layer 312a and the second thermal extension layer 312b may be arranged complementary to each other.

[0112] The waveguide array 310 may include a plurality of waveguides with a pre-determined phase relationship defined for light propagating through the plurality of waveguides. The plurality of waveguides may be arranged at least substantially parallel relative to each other. The plurality of waveguides may be arranged spaced apart from each other.

[0113] The first thermal heater 314a may include a plurality of first heater elements overlapping with the first thermal extension layer 312a and the first portion of the waveguide array 310. The plurality of first heater elements may be arranged at least substantially parallel relative to each other. The plurality of first heater elements may be arranged spaced apart from each other. The plurality of first heater elements may have different lengths such that the first thermal heater 314a may be arranged in a triangular shape. The first thermal extension layer 312a may have a triangular shape.

[0114] The second thermal heater 314b may include a plurality of second heater elements overlapping with the second thermal extension layer 312b and the second portion of the waveguide array 310. The plurality of second heater elements may be arranged at least substantially parallel relative to each other. The plurality of second heater elements may be arranged spaced apart from each other. The plurality of second heater elements may have different lengths such that the second thermal heater 314b may be arranged in a triangular shape. The second thermal extension layer 312b may have a triangular shape.

[0115] The waveguide array 310 may be coupled (e.g. mechanically and/or optically coupled) to the plurality of input waveguides 304 and the plurality of output waveguides 306 such that light may propagate through the plurality of input waveguides 304, the waveguide array 310 and the plurality of output waveguides 306. In various embodiments, the plurality of input waveguides 304 may be coupled to the waveguide array 310 via a first coupler (e.g. star coupler) 352, while the plurality of output waveguides 306 may be coupled to the waveguide array 310 via a second coupler (e.g. star coupler) 354.

[0116] The optical structure 360 may further include a first conductive interconnect 316a and a second conductive interconnect 316b coupled to the first thermal heater 314a for the supply of an electrical signal to the first thermal heater 314a to operate the first thermal heater 314a to generate heat for thermal tuning of the waveguide structure 302.

[0117] The optical structure 360 may further include a third conductive interconnect 316c and a fourth conductive interconnect 316d coupled to the second thermal heater 314b for the supply of an electrical signal to the second thermal heater 314b to operate the second thermal heater 314b to generate heat for thermal tuning of the waveguide structure 302.

[0118] By having separate and independent first thermal heater 314a and second thermal heater 314b, different portions of the waveguide structure 302 may be thermally tuned. Therefore, light propagating through the first portion and the second portion of the waveguide array 310 may be individually tuned by means of the heat generated by the first thermal heater 314a and/or the second thermal heater 314b, thereby providing a higher degree of thermal tuning.

[0119] In various embodiments, during operation of the respective optical structures 300, 320, 330, 350, 360, the waveguide structure 302 may be thermally controlled or thermally tuned to compensate for a phase error that may be induced between the input light received by the plurality of input waveguides 304 and the light coupled out of the optical structure 300 by the plurality of output waveguides 306.

[0120] It should be appreciated that in any one of the optical structures 300, 320, 330, 350, 360, the thermal heater 314 may be a single heater element arranged in a meander pattern or may include a plurality of heater elements, which may be arranged at least substantially parallel to each other and/or spaced apart from each other. In addition, the thermal heater may have any shape, including for example trapezoidal or triangular.

[0121] FIG. 4A shows a top view of an optical structure 400 before thermal tuning, while FIG. 4B shows a top view of the optical structure 400 after thermal tuning, according to various embodiments. FIGS. 4A and 4B illustrate the application of the waveguide structure of various embodiments in an optical waveguide array, for fine tuning in an AWG.

[0122] The optical structure (e.g. AWG) 400 may include a waveguide structure 401. The waveguide structure 401 may include a waveguide array 402 monolithically integrated on a support substrate (not shown). The waveguide array 402 may include a plurality of waveguides. As an example as shown in FIGS. 4A and 4B, the waveguide array 402 may include six optical waveguides. The waveguide structure 401 may include a thermal extension layer 412 monolithically integrated on the support substrate (not shown). The thermal extension layer 412 may be arranged over a portion of the waveguide array 402. The waveguide structure 401 may further include a thermal heater (omitted for ease of understanding of FIGS. 4A and 4B) monolithically integrated on the support substrate (not shown). The thermal heater may be arranged over the thermal extension layer 412.

[0123] The waveguide array 402 may be coupled (e.g. mechanically and/or optically coupled) to a plurality of output waveguides 406 via a coupler (e.g. star coupler) 432. The plurality of output waveguides 406 may include a first output waveguide 452, a second output waveguide 454, a third output waveguide 456 and a fourth output waveguide 458.

[0124] In a general silicon-on-insulator (SOI) AWG, the output wavelengths may be mismatch with request, which for example may be caused by fabrication mismatching tolerance, and/or stress influence and/or temperature fluctuation. As illustrated in FIG. 4A, there may be deviation in the propagation of light of different wavelengths caused by phase error. For example, light of blue wavelength as represented by 442 may not be optimally directed to the first waveguide 452 for coupling out of the optical structure 400. Similarly, light of green wavelength as represented by 444 may not be optimally directed to the second waveguide 454, light of yellow wavelength as represented by 446 may not be optimally directed to the third waveguide 456, and light of red wavelength as represented by 448 may not be optimally directed to the fourth waveguide 458.

[0125] FIG. 4B shows the optical structure 400 after thermal control or tuning of the waveguide array 402 to compensate for the phase error. Heat generated by the thermal heater (not shown) may be at least substantially uniformly distributed by the thermal extension layer 412 onto the waveguide array 402. This may allow tuning of the propagation of light of different wavelengths through the optical structure 400. As a non-limiting example, therefore, thermal tuning may enable light of blue wavelength 442 to be optimally directed to the first waveguide 452 for coupling out of the optical structure 400. Similarly, light of green wavelength 444 may be optimally directed to the second waveguide 454, light of yellow wavelength 446 may be optimally directed to the third waveguide 456, and light of red wavelength 448 may be optimally directed to the fourth waveguide 458.

[0126] Results relating to the waveguide structures of various embodiments will now be described by way of the following non-limiting examples. In the examples, titanium nitride (TiN) is used as the thermal heater and aluminium (Al) is used as the thermal or heat extension layer. Simulation of results may be carried out based on numerical analysis.

[0127] FIG. 5A shows a plot 500 of simulated temperature distribution of a waveguide structure without a thermal extension layer, while FIG. 5B shows a plot 502 of simulated temperature distribution of a waveguide structure with a thermal extension layer, according to various embodiments. In FIGS. 5A and 5B, the thermal heater is indicated as dashed lines in the vicinity of Y = 0. In FIG. 5B, the thermal extension layer is indicated as a thick solid line just below the thermal heater, in the vicinity of Y = 0. Comparison of the results illustrated in FIGS. 5A snd 5B show that for a waveguide structure without a thermal extension layer, temperature fluctuation may be larger than that of a waveguide structure with an Al thermal extension layer. Furthermore, as shown in FIG. 5B, at least substantially uniform temperature distribution may be achieved by using a heat extension layer. Therefore, without a thermal expansion layer, temperature may fluctuate in the arrayed waveguide layer, which may cause varied phase change to every arrayed waveguide. With a thermal expansion layer, temperature may be distributed very smoothly in the waveguide layer, which may cause at least substantially identical phase change to every arrayed waveguide.

[0128] FIG. 6 shows a plot 600 of simulated temperature distribution results for aluminium (Al) thermal extension layers of different thicknesses, according to various embodiments. The results shown in FIG. 6 are for a waveguide structure where the spacing or gap between the thermal extension layer and the thermal heater is about 200 nm. Plot 600 shows result 602 where there is no thermal extension layer, result 604 where the Al thermal extension layer has a thickness of about 100 nm, result 606 where the Al thermal extension layer has a thickness of about 200 nm, and result 608 where the Al thermal extension layer has a thickness of about 250 nm. As may be observed from plot 600, the thicker the thermal extension layer is, the more uniform the temperature distribution is in the waveguide layer, which is arranged beneath the thermal extension layer.

[0129] FIG. 7 shows a plot 700 of simulated light propagation through a waveguide structure of various embodiments. In plot 700, the output light 702 may be in a direction at least substantially parallel to the propagation direction of the input light 704.

[0130] FIGS. 8A to 8L show respective plots of simulated light propagation through a waveguide structure of various embodiments, illustrating the phase array of various embodiments for light wave direction controlling. The direction may be changed by changing the phase of the light as a result of thermo-optical tuning. As shown in FIGS.8A to 8L, the propagation direction of the output light wave 802 may be controlled to deviate relative to a central axis of the waveguide structure or to the propagation direction of the input light 804. Results are shown in FIGS. 8A to 8L for deviation of the output light wave 802 of between 0° and 110°, at an interval of 10°.

[0131] As described above, various embodiments may provide thermally tunable optical devices or phase arrays with uniform temperature distributions. Such optical phase arrays may be used for tunable arrayed waveguide grating (AWG), and reconfigurable optical switches for wavelength division multiplexing (WDM) applications. Such optical devices may be directly used for telecommunication and computer communication.

[0132] Various embodiments may include one or more of the following : (1) a silicon-on-insulator (SOI) based device or structure which may provide a lower cost (cost effective), a smaller size and higher integration of components; (2) electrical control of the waveguide structure and/or optical structure; (3) a heater array with a thermal extension layer, which may provide at least substantially uniform temperature distribution; (4) heater strips that may be equal-different, where the heater lengths may be of an arithmetic sequence, and which may be arranged with equal spacings between adjacent heater strips; (5) a planar thermal expansion layer under the heater strips; (6) planar integration with CMOS compatible fabrication processes for implementation or realisation.

[0133] It should be appreciated that modifications to the waveguide structure and/or the optical structure of various embodiments may be carried out to realise a compact footprint. In addition, multiple function integration may also be incorporated. Furthermore, various embodiments may be employed in a bio/chemical sensor.

[0134] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A waveguide structure comprising:

a support substrate;

a waveguide array disposed on the support substrate;

a thermal extension layer disposed over the waveguide array; and

a thermal heater disposed over the thermal extension layer;

wherein the thermal extension layer has a high thermal conductivity sufficient to uniformly distribute the generated heat from the thermal heater to the waveguide array; and

wherein the waveguide array, the thermal extension layer and the thermal heater are monolithically integrated on the support substrate.

2. The waveguide structure of claim 1, wherein the waveguide array comprises a plurality of waveguides extending substantially parallel and spaced apart from each other.

3. The waveguide structure of claim 2, wherein each of the plurality of waveguides is spaced apart from another of the plurality of waveguides at a fixed interval.

4. The waveguide structure of claim 2, wherein each of the plurality of waveguides is spaced apart from another of the plurality of waveguides at a varying interval.

5. The waveguide structure of claim 1, wherein the thermal heater comprises a plurality of heater elements extending substantially parallel and spaced apart from each other.

6. The waveguide structure of claim 5, wherein each of the plurality of heater elements is spaced apart from another of the plurality of heater elements at a fixed interval.

7. The waveguide structure of claim 5, wherein each of the plurality of heater elements is spaced apart from another of the plurality of heater elements at a varying interval.

8. The waveguide structure of claim 1, wherein the thermal heater comprises a plurality of heater elements extending substantially parallel and spaced apart from each other at a fixed interval, and wherein the waveguide array comprises a plurality of waveguides extending substantially parallel and spaced apart from each other at a varying interval.

9. The waveguide structure of claim 1, wherein the thermal extension layer comprises a thickness in a range of about 100 nm to about several microns.

10. The waveguide structure of claim 1, wherein the thermal extension layer comprises aluminium, copper, or silicon.

11. An optical structure comprising:

a plurality of input waveguides configured to receive an input light;

a plurality of output waveguides configured to couple light out of the optical structure; and

a waveguide structure of claim 1 coupled between the plurality of input waveguides and the plurality of output waveguides.

12. The optical structure of claim 11, wherein the waveguide structure is configured to be thermally controlled to compensate for a phase error between the input light and the light out of the optical structure.

13. The optical structure of claim 12, further comprising:

a first coupler arranged between the plurality of input waveguides and an input end of the waveguide structure; and a second coupler arranged between an output end of the waveguide structure and the plurality of output waveguides.

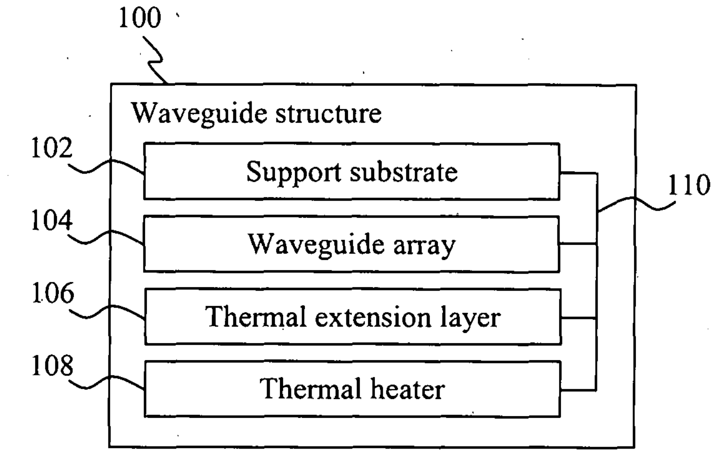


FIG. 1A

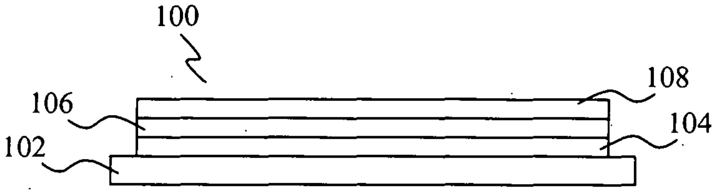


FIG. 1B

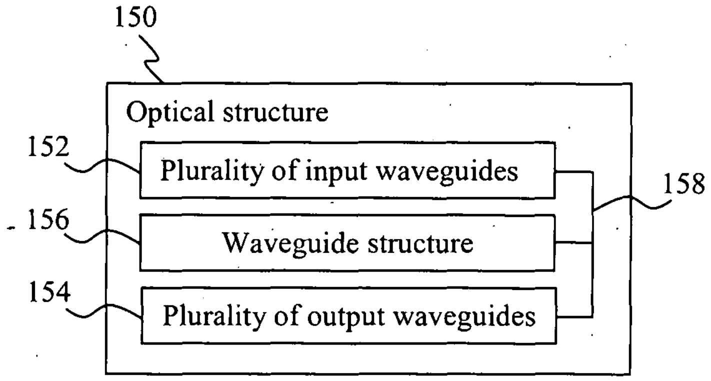


FIG. 1C

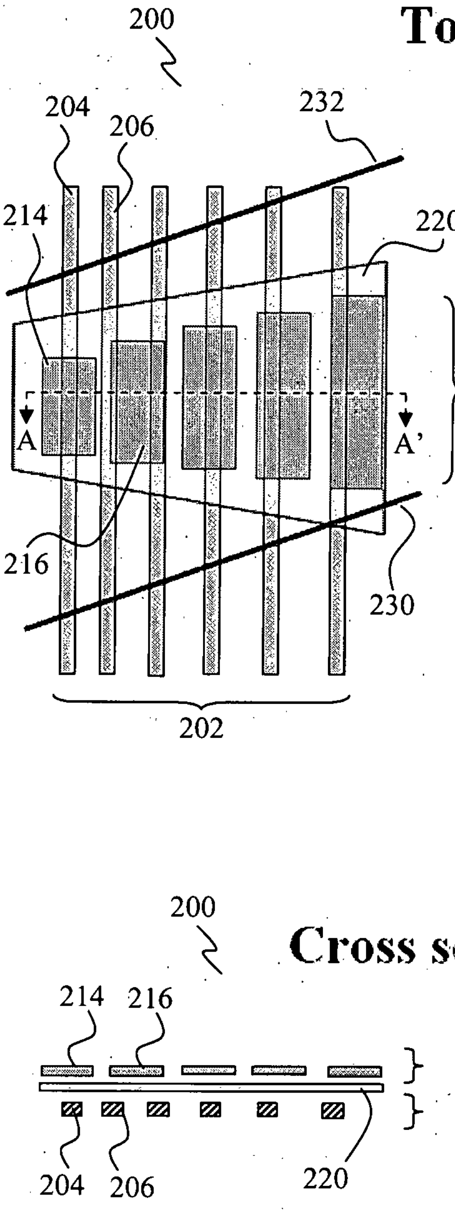

Top view
200
204
206
232
214
220
212
A
A'
216
230
202
Cross section view
200
214
216
212
202
204
206
220

FIG. 2A

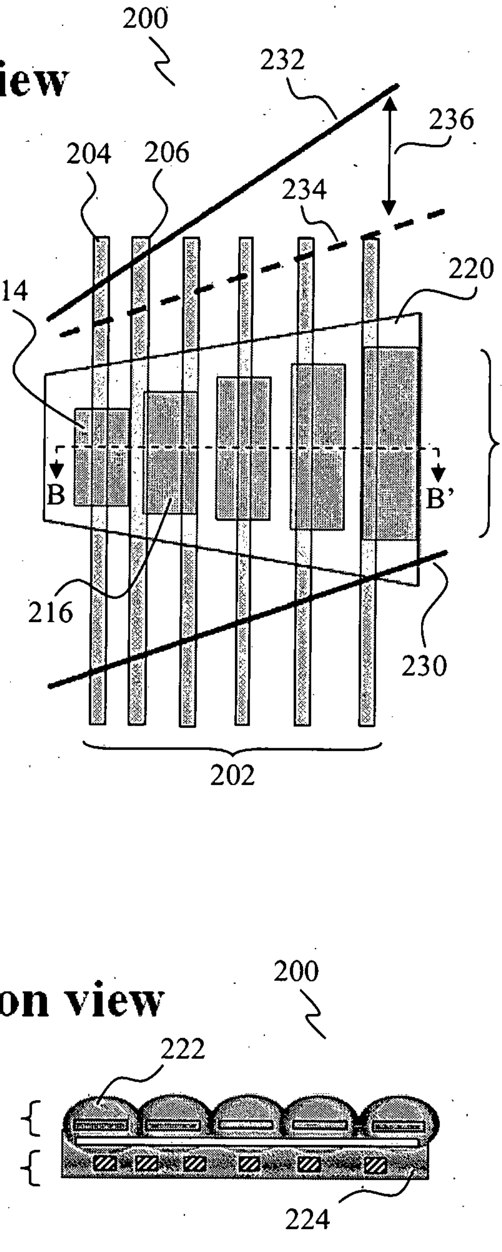

200
232
236
204
206
234
214
220
212
B
B'
216
230
202
200
222
212
202
224

FIG. 2B

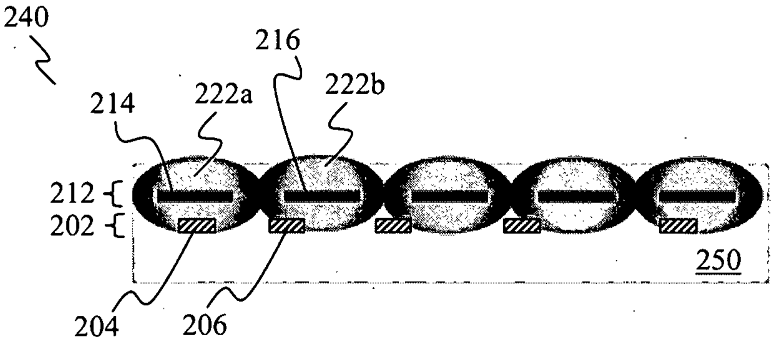


FIG. 2C

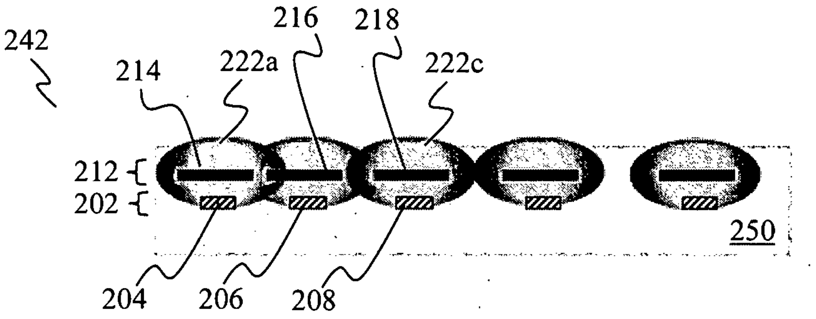


FIG. 2D

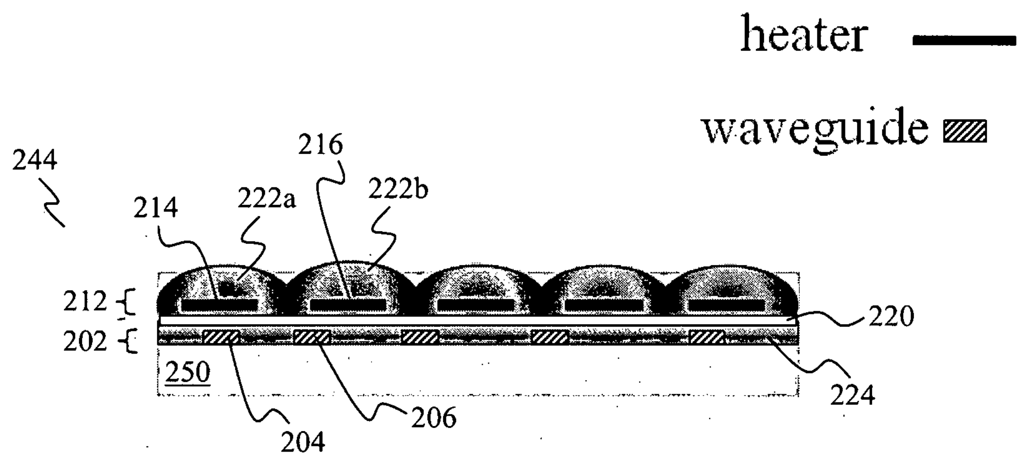


FIG. 2E

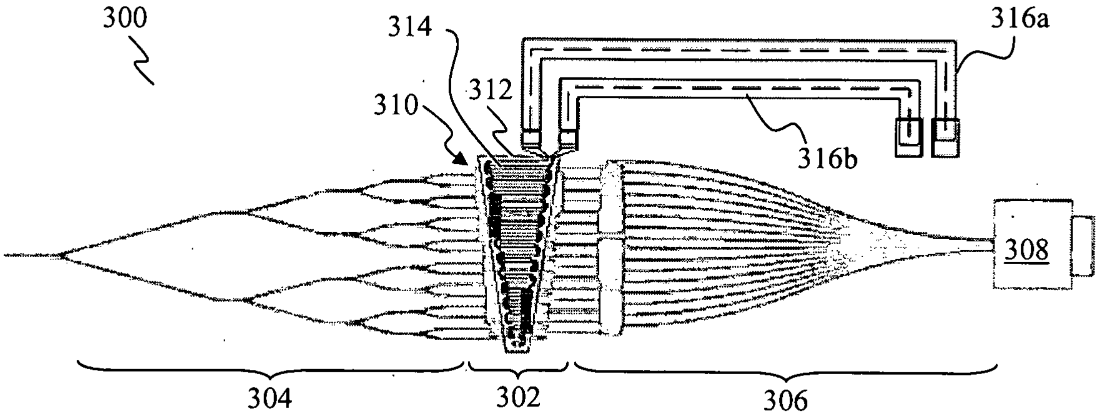


FIG. 3A

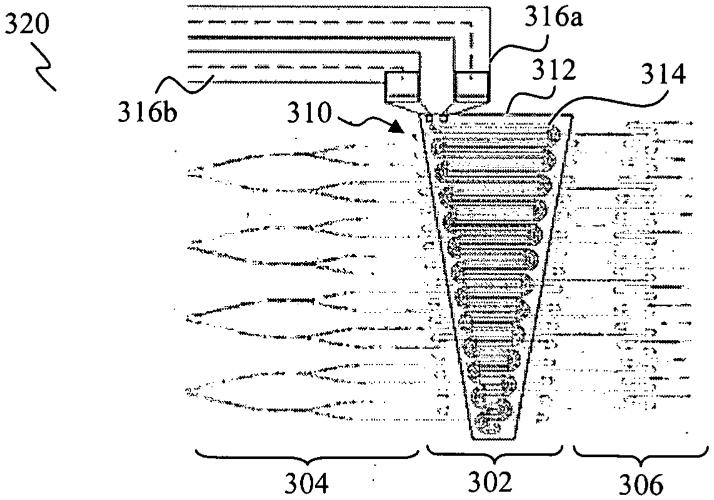


FIG. 3B

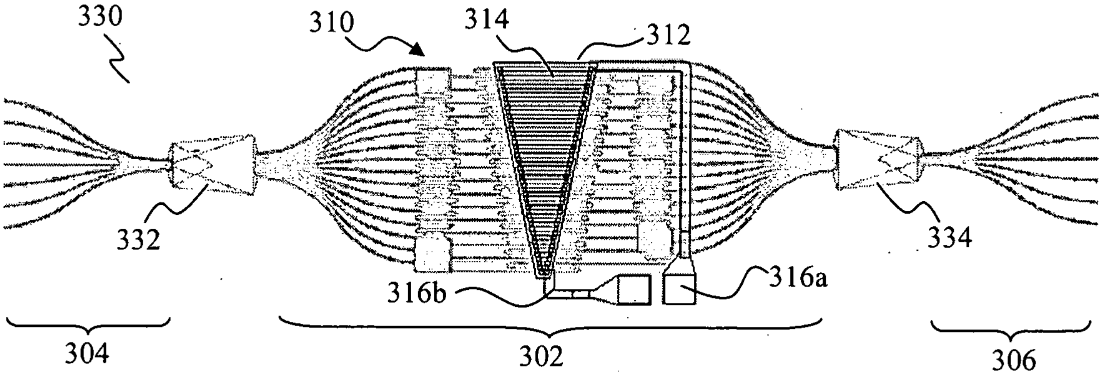


FIG. 3C

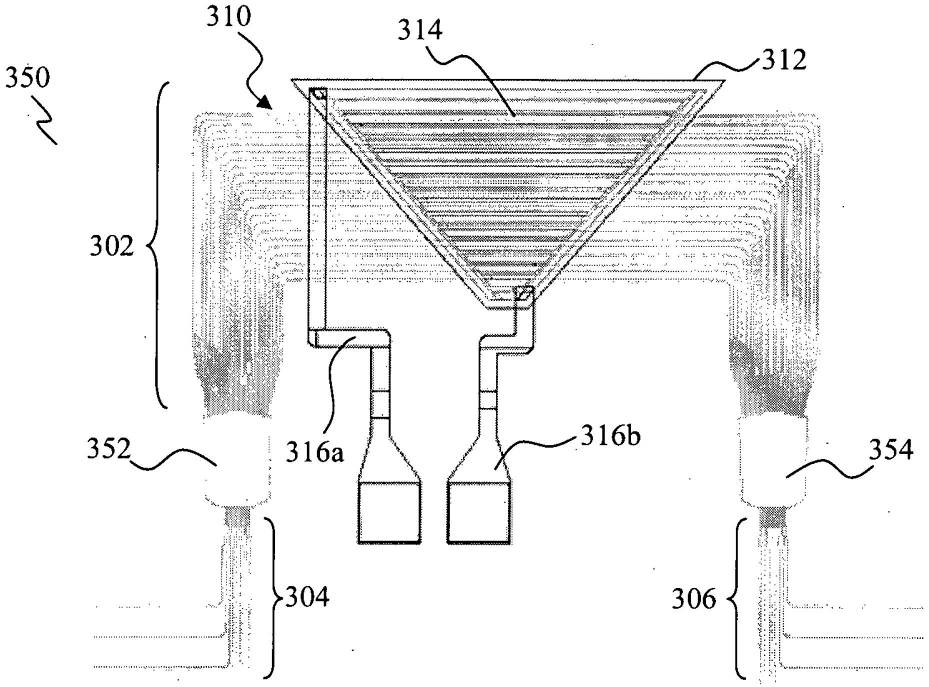

310
350
314
312
302
316a
316b
352
354
304
306

FIG. 3D

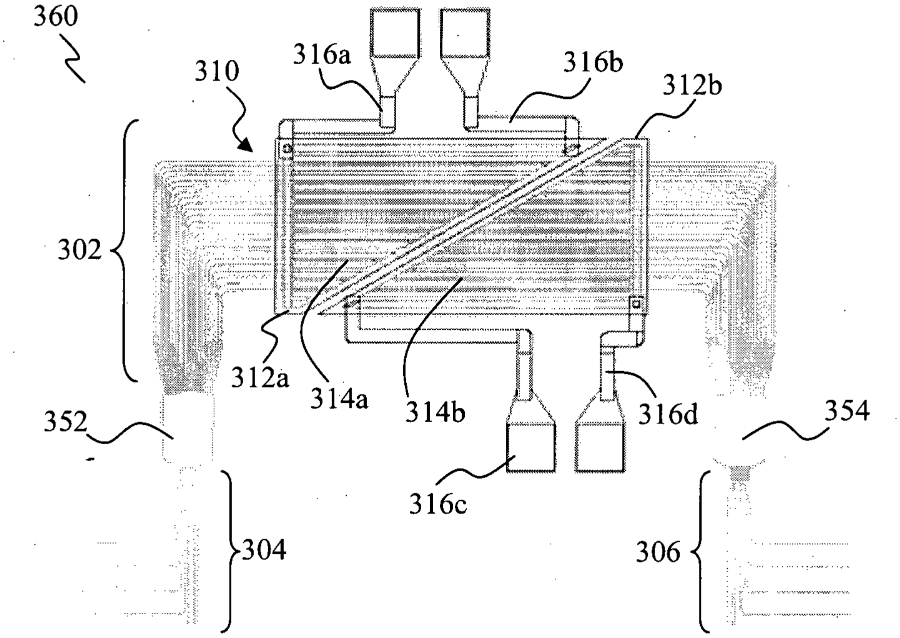

360
316a
316b
312b
310
302
312a
314a
314b
316d
316c
352
354
304
306

FIG. 3E

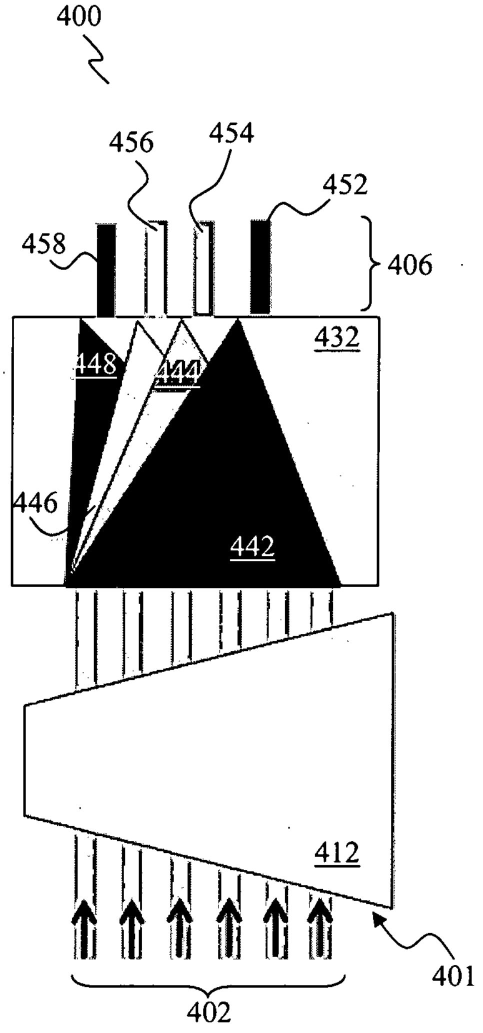

400
456
454
452
458
406
432
448
444
446
442
412
401
402

FIG. 4A

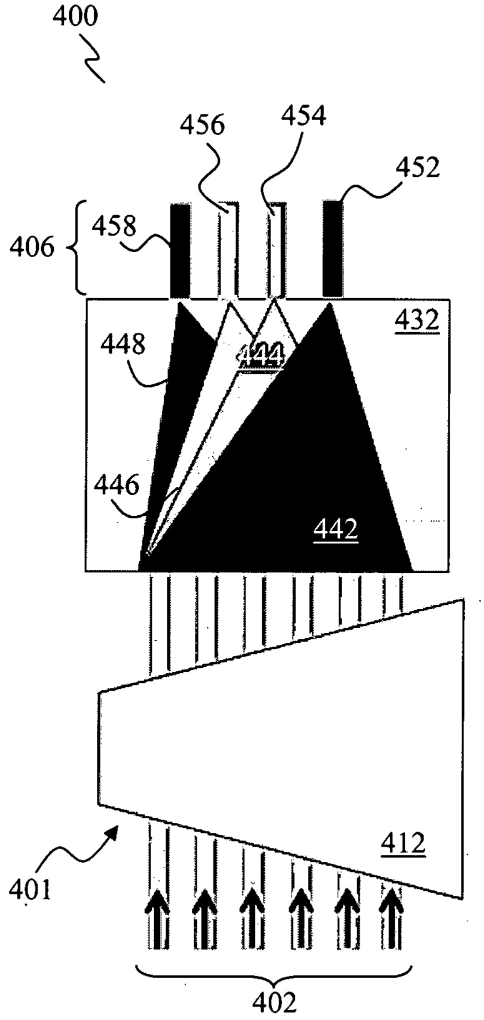

400
456
454
452
406
458
432
448
444
446
442
401
412
402

FIG. 4B

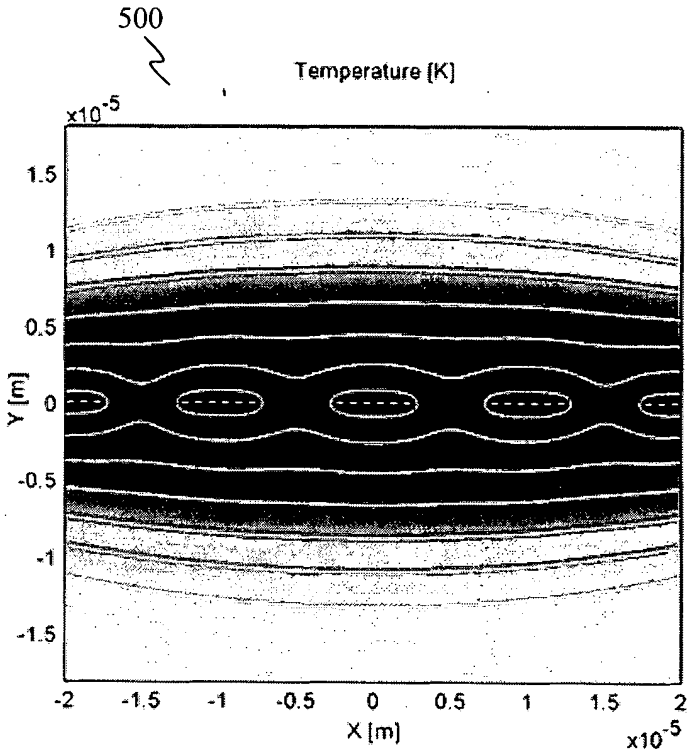

500
Temperature [K]
x10^-5
1.5
1
0.5
0
-0.5
-1
-1.5
Y [m]
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
X [m]
x10^-5

FIG. 5A

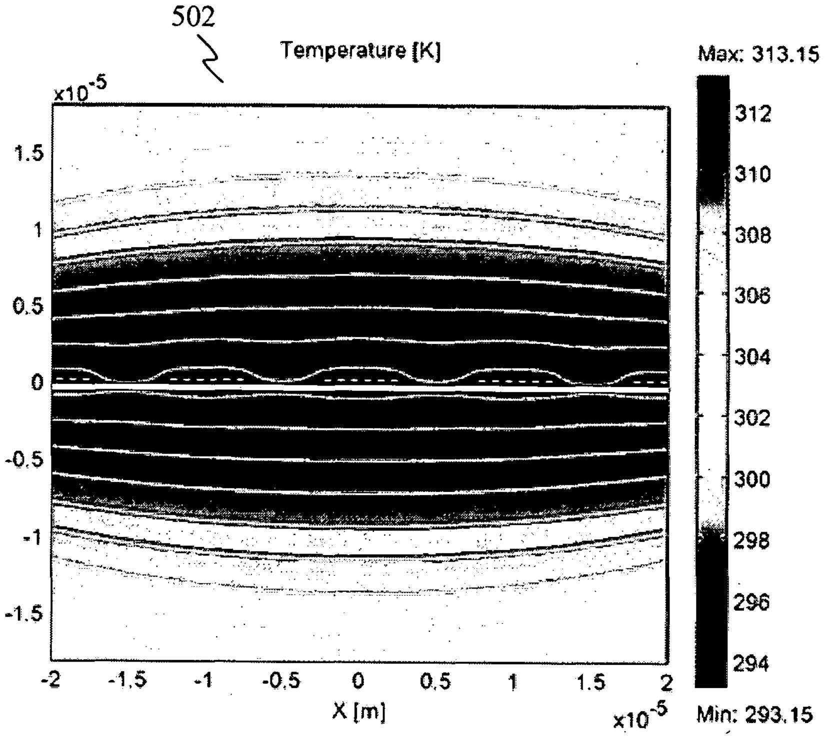

502
Temperature [K]
x10^-5
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
X [m]
x10^-5
Max: 313.15
312
310
308
306
304
302
300
298
296
294
Min: 293.15

FIG. 5B

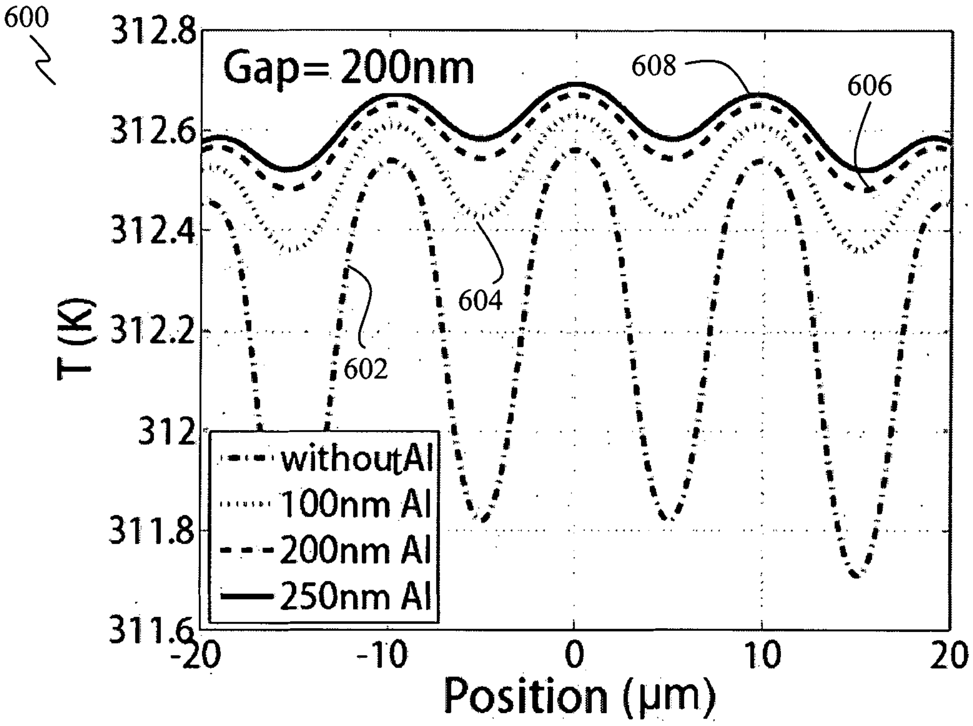

600
Gap= 200nm
608
606
604
602
T (K)
312.8
312.6
312.4
312.2
312
311.8
311.6
-20
-10
0
10
20
Position (μm)
withoutAl
100nm Al
200nm Al
250nm Al

FIG. 6

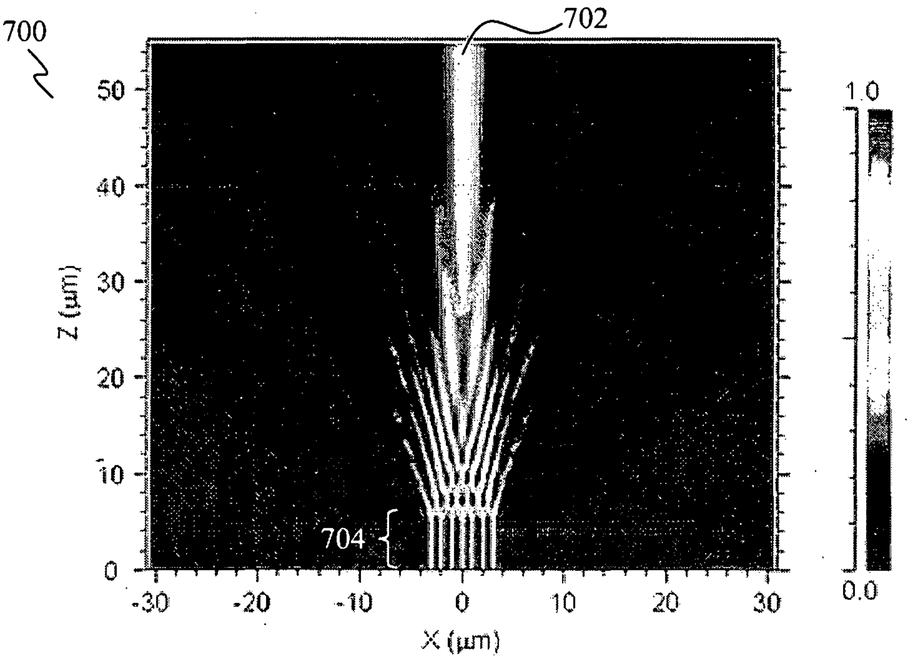

700
702
704
Z (μm)
50
40
30
20
10
0
-30
-20
-10
0
10
20
30
X (μm)
1.0
0.0

FIG. 7

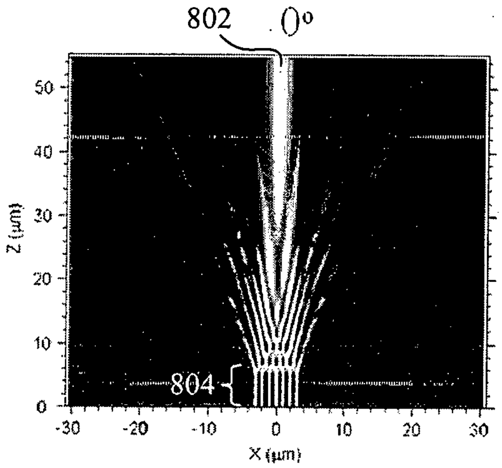


FIG. 8A

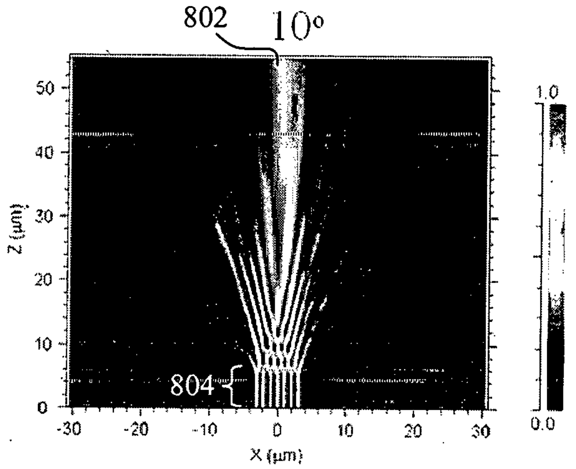


FIG. 8B

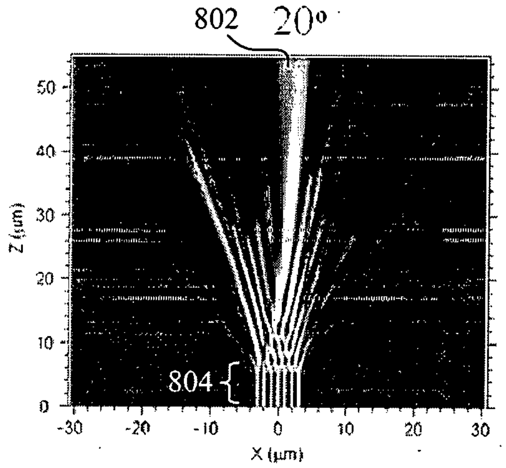


FIG. 8C

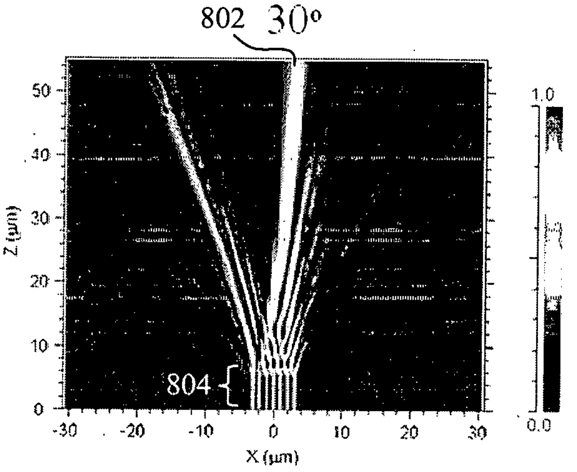


FIG. 8D

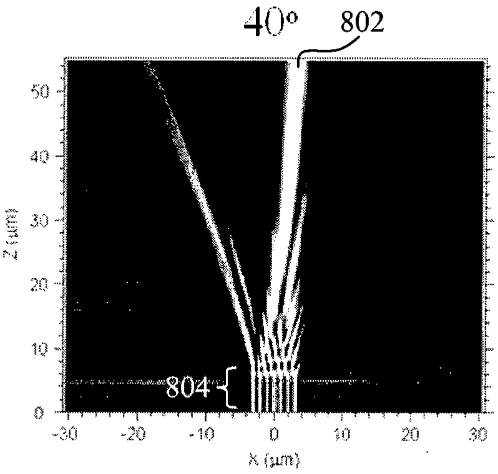


FIG. 8E

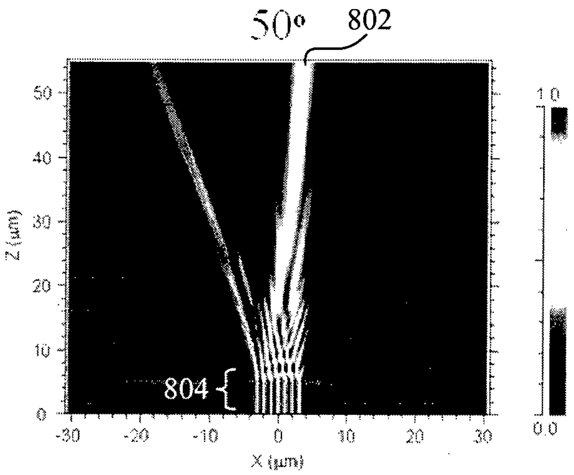


FIG. 8F

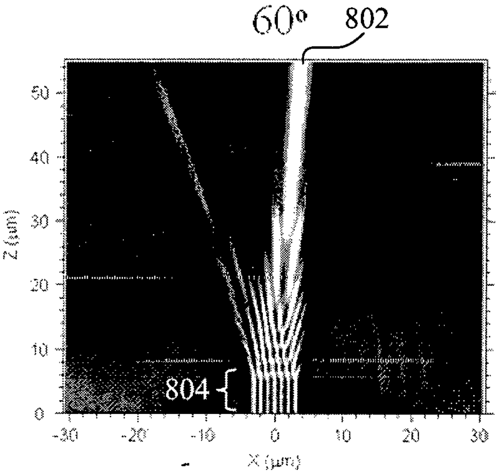


FIG. 8G

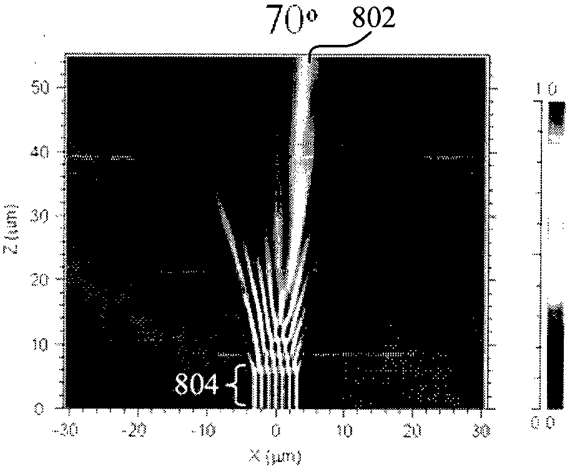


FIG. 8H

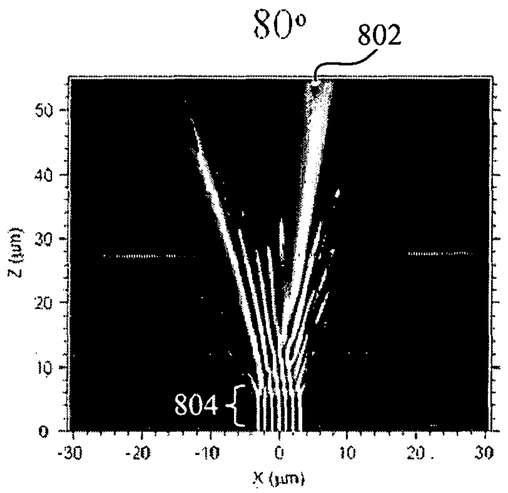


FIG. 8I

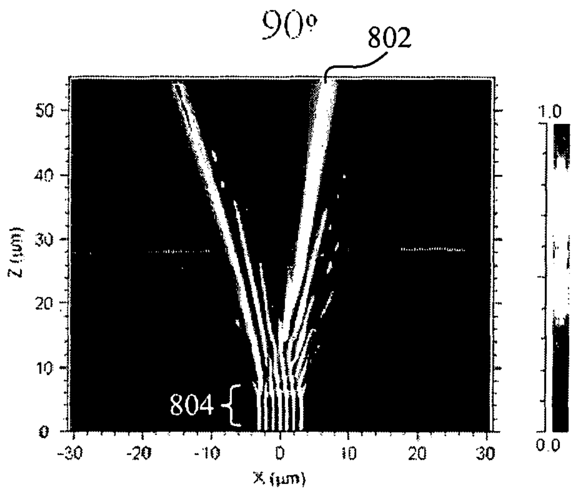


FIG. 8J

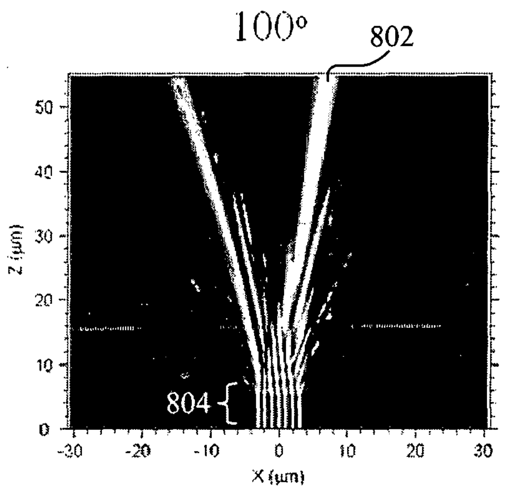


FIG. 8K

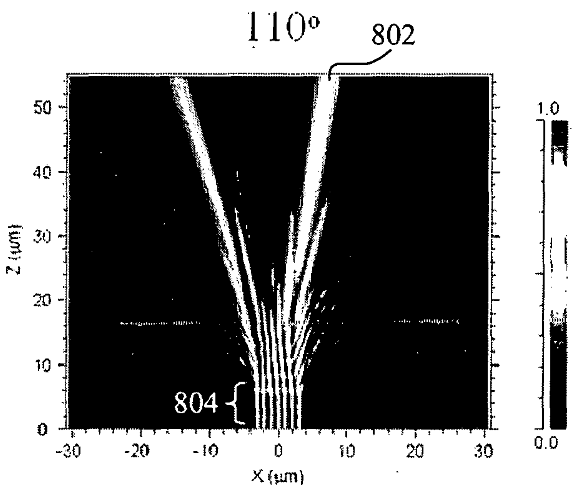


FIG. 8L

INTERNATIONAL SEARCH REPORT	International application No. **PCT/SG2013/000361**

A. CLASSIFICATION OF SUBJECT MATTER

G02B 6/35 (2006.01) G02F 1/035 (2006.01) G02B 6/12 (2006.01)

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)

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)

Databases : WPI, EPODOC, TXTUS5, INSPEC & keywords:
waveguide, AWG, heat, thermal, temperature, monolithic, integrated, CMOS, tuning, switching, layer, film, plate, foil, conductive, spread, distribute and similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

☒ Further documents are listed in the continuation of Box C ☒ See patent family annex

*	Special categories of cited documents:		
"A"	document defining the general state of the art which is not considered to be of particular relevance	"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
"E"	earlier application or patent but published on or after the international filing date	"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
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"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
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 10 October 2013	Date of mailing of the international search report 10 October 2013
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustralia.gov.au Facsimile No.: +61 2 6283 7999	**Authorised officer** Jayati Ray AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262223654

INTERNATIONAL SEARCH REPORT C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT	International application No. **PCT/SG2013/000361**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005/0135743 A1 (ASCANIO ET AL.,) 23 June 2005 Fig. 9, paragraphs 0042, 0045	1-13
X	KR 1020020043415 A (JONG-DAE PARK) 10 June 2002 Fig. 1 and the associated text	1-13
X	JP 2001-116936 A (HITACHI CABLE LTD) 27 April 2001 Figs. 1, 5, paragraphs 0016-0019	1-13

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/SG2013/000361**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		**Patent Family Member/s**	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
US 2005/0135743 A1	23 Jun 2005	US 7088887 B2	08 Aug 2006
		WO 2005062935 A2	14 Jul 2005
KR 1020020043415 A	10 Jun 2002	None	
JP 2001-116936 A	27 Apr 2001	JP 4088002 B2	21 May 2008

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.