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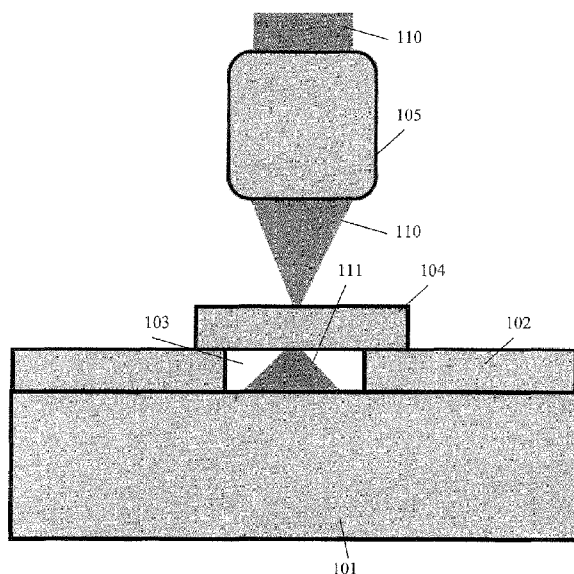
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(54) Title: SYSTEMS AND METHODS FOR CHIP-INTEGRATED INFRARED SILICON DETECTOR

FIG. 1



(57) Abstract: Systems and methods for chip-integrated infrared silicon detectors are disclosed. In one aspect of the disclosed subject matter, a detector for detecting at least one electromagnetic field is disclosed. An exemplary detector can include a photodetector, a photonic crystal cavity, a spacer layer, and an incoupling element. The spacer layer can be disposed between the photonic crystal cavity and the photodetector. The incoupling element can be adapted to couple at least one input electromagnetic field into the photonic crystal cavity. The photonic crystal cavity can be adapted to upconvert the at least one input electromagnetic field to form at least one output electromagnetic field, thereby permitting detection of the at least one output electromagnetic field by the photodetector through the spacer layer. In another aspect, a method for upconverting an input field is disclosed. In another aspect, a method for integrating a photonic crystal cavity onto a photodetector is disclosed.

SYSTEMS AND METHODS FOR CHIP-INTEGRATED INFRARED SILICON DETECTOR

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

5 This invention is made with government support under Award Number FA9550-11-1-0014 awarded by the Air Force Office of Scientific Research. The Government has certain rights in the invention.

CROSS REFERENCE TO RELATED APPLICATION

10 This application claims priority from U.S. Provisional Application No. 61/618,365, filed March 30, 2012, which is incorporated by reference herein.

BACKGROUND

15 The disclosed subject matter relates to techniques for chip-integrated infrared silicon detectors.

 Semiconductor photodetectors, such as silicon diode photodetectors, can provide improved timing resolution, quantum efficiency, low dark counts, fast reset time, and/or single photon detection using avalanche processes. However, silicon diode photodetectors can be ineffective for photons having an energy below
20 the silicon bandgap, or wavelengths above about 1.1 μ m. Smaller-bandgap semiconductor photodetectors such as indium gallium arsenide (InGaAs) or germanium (Ge) can be similarly ineffective. Accordingly, an infrared signal field can undergo nonlinear upconversion so that the upconverted field can be above the semiconductor bandgap, and thus can be detected with a semiconductor photodiode.

25 A nonlinear crystal, such as lithium niobate (LiNbO₃) or Potassium Titanium Oxide Phosphate (KTP), can be used, and can include a periodically poled crystal direction for improved phase matching and upconversion efficiency. However, there exists a need for an improved device for upconversion and detection of electromagnetic fields.

SUMMARY

Systems and methods for chip-integrated infrared silicon detectors are disclosed herein.

In one aspect of the disclosed subject matter, a device for detecting at least one electromagnetic field is disclosed. An exemplary detector can include a photodetector, a photonic crystal cavity, a spacer layer, and an incoupling element. The spacer layer can be disposed between the photonic crystal cavity and the photodetector. The incoupling element can be adapted to couple at least one input electromagnetic field into the photonic crystal cavity. The photonic crystal cavity can be adapted to upconvert the at least one input electromagnetic field to form at least one output electromagnetic field, permitting detection of the at least one output electromagnetic field by the photodetector through the spacer layer.

In some embodiments, the photodetector can be a silicon (Si) photodetector or a Si avalanche photodiode (APD). In some embodiments, the spacer layer can include a layer of low-index material. For example, the spacer layer can be a polymer layer. In some embodiments, the spacer layer can have at least one air hole disposed between at least a portion of the photonic crystal cavity and the photodetector, enhancing a total internal reflection within the photonic crystal cavity at a boundary between the photonic crystal cavity and the at least one air hole.

In some embodiments, the spacer layer can include an asymmetric cladding at least partially covering at least one side of the photonic crystal cavity. For example, the asymmetric cladding can be a polymer cladding. In some embodiments, a longpass filter can be disposed on the photonic crystal opposite the photodetector.

In some embodiments, the incoupling element can be a lens, a tapered fiber, or an in-plane waveguide, and can be adapted to couple the at least one input electromagnetic field into at least one resonance mode of the photonic crystal cavity.

In some embodiments, the photonic crystal cavity can have first and second resonance modes. A beam pump can be coupled to the incoupling element. A pump field from the beam pump can couple into the first resonance mode and the at least one input field can couple into the second resonance mode. The photonic crystal cavity can be adapted to cause a parametric upconversion to generate at least two output electromagnetic fields, permitting detection of at least one of the output electromagnetic fields by the photodetector through the spacer layer.

In another aspect of the disclosed subject matter, a method for upconverting an input field is disclosed. An exemplary method can include receiving the input field, and coupling the received field into a photonic crystal cavity, upconverting the input field to form an output field. The output field can be radiated
5 through a spacer layer into a photodetector.

In some embodiments, the input field can be upconverted by second harmonic generation such that the output field has a wavelength that is one half of the wavelength of the input field. For example, the wavelength of the input field can be 1.5 μm , and the wavelength of the output field can be 775 nm.

10 In some embodiments, the input field can include two or more time separated pulses. The input field can be upconverted in the photonic crystal cavity such that the photonic crystal cavity acts as an optical autocorrelator.

In another aspect of the disclosed subject matter, a method for integrating a photonic crystal cavity onto a photodetector is disclosed. An exemplary
15 method can include fabricating a spacer layer on a first host chip. The spacer layer can be transferred onto a photodetector. A photonic crystal cavity can be fabricated on a second host chip. The photonic crystal cavity can be transferred onto the spacer layer. An incoupling element can be adapted to couple at least one electromagnetic field into the photonic crystal cavity.

20 In some embodiments, the photonic crystal cavity can be transferred by elastomer stamping. In some embodiments, the spacer layer can be an asymmetric cladding layer. In some embodiments, the spacer layer can have at least one air hole formed therein. In some embodiments, a beam pump can be coupled to the incoupling element.

25 The accompanying drawings, which are incorporated and constitute part of this disclosure, illustrate embodiments of the disclosed subject matter and serve to explain the principles of the disclosed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

30 FIG. 1 shows an example photonic crystal cavity integrated onto a photodetector in accordance with some embodiments of the disclosed subject matter.

FIG. 2 shows an example photonic crystal cavity integrated onto a photodetector in accordance with some embodiments of the disclosed subject matter.

FIG. 3 shows an example photonic crystal cavity integrated onto a photodetector in accordance with some embodiments of the disclosed subject matter.

FIG. 4 shows an example photonic crystal cavity integrated onto a photodetector in accordance with some embodiments of the disclosed subject matter.

5 FIG. 5 shows an example method for upconverting an input field in accordance with some embodiments of the disclosed subject matter.

FIG. 6 shows an example method for integrating a photonic crystal cavity onto a photodetector in accordance with some embodiments of the disclosed subject matter.

10 Throughout the drawings, similar reference numerals and characters, unless otherwise stated, are used to denote like features, elements, components or portions of the illustrated embodiments. Moreover, while the disclosed subject matter will now be described in detail with reference to the FIGS., it is done so in connection with the illustrative embodiments.

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DETAILED DESCRIPTION

The disclosed subject matter provides systems and methods for chip-integrated infrared silicon detectors. Photonic crystal (PC) cavities can enhance the upconversion efficiency of on-resonance input light, which has a wavelength of a resonant mode of the PC cavity. The detection spectral range of a silicon photodetector can be below 1.1 μm in wavelength, which can be limited by the material bandgap. The disclosed subject matter provides techniques for integrating a PC cavity onto a photodetector. By way of example and not limitation, the PC cavity can upconvert relatively long wavelength (e.g. infrared light) into shorter wavelength (e.g. visible light), which can then be detected by a silicon photodetector.

25 Referring to FIG. 1 and FIG. 6, a spacer layer 102 can be fabricated on a host chip (not pictured) (601). The spacer layer 102 can be transferred onto a photodetector 101 (602). The photodetector 101 can be any suitable photodetector. By way of example and not limitation, the photodetector 101 can be a silicon (Si) photodetector or a Si avalanche photodiode (APD). Alternatively, by way of example and not limitation, the photodetector 101 could be an indium gallium arsenide (InGaAs) photodetector or a germanium (Ge) photodetector.

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A PC cavity 104 can be fabricated on a host chip (not pictured) (603). The PC cavity 104 can be transferred onto the spacer layer 102 (604). Thus the spacer layer 102 can be disposed between the PC cavity 104 and the photodetector 101. By way of example and not limitation, the PC cavity 104 can be transferred onto
5 the spacer layer 102 by elastomer stamping, as described below (604).

The spacer layer 102 can have at least one air hole 103 formed therein. The at least one air hole 103 can be disposed between at least a portion of the PC cavity 104 and the photodetector 101, thereby enhancing total internal reflection (TIR) within the PC cavity 104 at the boundary between the PC cavity 104 and the at
10 least one air hole 103. In some embodiments, the spacer layer 102 can be a layer of low-index material. As used herein "low-index" refers to an index of refraction that is sufficiently lower than the index of refraction of the PC cavity 104 to allow for efficient TIR at the boundary between the spacer layer 102 and the PC cavity 104. By way of example and not limitation, the PC cavity 104 can be fabricated in gallium
15 phosphide (GaP) or gallium arsenide (GaAs) materials, which have a high second nonlinear coefficient and a refractive index greater than 3. The high second nonlinear coefficient can enable a high upconversion efficiency of the input electromagnetic field 110, and thereby generates a stronger output field 111. In such cases, a low-index material for the spacer layer 102 can be a material with a refractive index less
20 than 2. In such cases, by way of example and not limitation, a low index material can be silicon dioxide (SiO₂) or a suitable polymer such as poly(methyl methacrylate) (PMMA). By way of example and not limitation, the spacer layer can have a thickness of 2-10 μm.

The spacer layer 102 can be fabricated (601) using known techniques. For example, the spacer layer 102 can be fabricated (601) and transferred (602) by
25 any of the techniques disclosed in commonly assigned U.S. Provisional Application Nos. 61/618,353 and 61/748,584, which are hereby incorporated by reference in their entirety. By way of example and not limitation, the spacer layer 102 can be fabricated (601) as follows. A 10 nm thick layer of polyvinyl alcohol (PVA) can be spin coated
30 onto a silicon host chip (not pictured). The spacer layer 102 of thickness 2-10 μm can be spin coated onto the PVA layer. If desired, one or more air holes 103 can be formed in the spacer layer 102 using any suitable technique such as electron beam lithography. The host chip can be submerged in water, thereby dissolving the layer of

PVA. Then the spacer layer 102 can be mechanically transferred onto the photodetector 101 (602).

The PC cavity 104 can be fabricated (603) using known techniques. For example, the PC cavity 104 can be fabricated (603) and transferred (604) by any of the techniques disclosed in commonly assigned U.S. Provisional Application Nos. 61/618,353 and 61/748,584, which are hereby incorporated by reference in their entirety. By way of example and not limitation, the PC cavity 104 can be fabricated (603) as follows. A host chip (not pictured) can include a top layer, a bottom layer, and a sacrificial layer disposed between the top and bottom layers. For example, the top and bottom layers can be GaP and the sacrificial layer can be aluminum gallium phosphide (AlGaP). The top layer can have a thickness of 140-250 nm. The sacrificial layer can have a thickness of 2 μm . The bottom layer can be a relatively thick substrate with a thickness of 500 μm . A resist layer can be spin coated onto the top layer. For example, the resist layer can be a polymer film, such as PMMA. A PC pattern can be formed in the resist layer by electron beam lithography. That PC pattern can then be formed in the top layer using the resist layer as a mask for dry chemical induced coupled plasmon etching, thereby forming a PC cavity 104 in the top layer. The resist layer can be dissolved. Then the host chip can be submerged in hydrofluoric (HF) acid, which can chemically etch the sacrificial AlGaP layer without damaging the top and bottom GaP layers. The PC cavity 104 can then be transferred onto the spacer layer 102 (604).

By way of example and not limitation, the PC cavity 104 can be transferred to the spacer layer 102 (604) by any of the techniques disclosed in commonly assigned U.S. Provisional Application No. 61/705,896, which is hereby incorporated by reference in its entirety. As used herein, "elastomer stamping" refers to any of the techniques for micro- and/or nano-device transfer disclosed in commonly assigned U.S. Provisional Application No. 61/705,896. For purpose of illustration and not limitation, such techniques can include using a metal tip covered with an elastomer to transfer the PC cavity 104 to the spacer layer 102. The metal tip can be formed from, for example, tungsten. The elastomer can include, for example, polydimethylsiloxanepolydime (PDMS). The elastomer-coated tip can be contacted with the PC cavity 104 such that the elastomer deforms and thereby creates a contact surface, thus attaching the PC cavity 104 to the tip via the adhesive force between the elastomer and the PC cavity 104. The tip can then be positioned over a predetermined

location of the spacer layer 102. For example, if the spacer layer 102 has one or more air holes 103, the PC cavity 104 can be positioned above the one or more air holes 103. The elastomer can relax to its original shape, thus decreasing the contact surface area, and releasing the PC cavity 104 onto the spacer layer 102 (604).

5 An incoupling element 105 can be adapted to couple at least one input electromagnetic field 110 into the photonic crystal cavity 104 (605). By way of example and not limitation, the incoupling element 105 can be a lens with high numerical aperture. By way of example and not limitation, the numerical aperture can be from 0.4 to 0.9. The PC cavity 104 can be adapted to upconvert the at least one
10 input electromagnetic field 110 to form at least one output electromagnetic field 111, permitting detection of the at least one output electromagnetic field 111 by the photodetector 101 through the spacer layer 102. The PC cavity 104 can have at least one resonance mode, and the incoupling element 105 can be adapted to couple the at least one input electromagnetic field 110 into the at least one resonance mode of the
15 PC cavity 104. For example, the incoupling element 105 can be adapted to couple the input field 110 into the PC cavity 104 by integrating a lens with high numerical aperture with the PC cavity 104 such that the input field 110 can be focused on and aligned with the PC cavity 104 resonance mode through free space.

 Referring to FIG. 1 and FIG. 5, by way of example and not limitation,
20 the incoupling element 105 can receive the input field 110 (501). The incoupling element 105 can couple the received input field 110 into a resonance mode of the PC cavity 104, thereby upconverting the input field 110 to form an output field 111 (502). The output field 111 can be radiated through the spacer layer 102 into the photodetector 101 (503). By way of example and not limitation, input field 110 can
25 be upconverted by second harmonic generation such that the output field 111 has a wavelength that is one half of a wavelength of the input field 110. For example, the wavelength of the input field 110 can be 1.5 μm , and the wavelength of the output field 111 can be 775 nm.

 By way of example and not limitation, the photodetector 101 can be an
30 InGaAs photodetector. An InGaAs photodetector can have a bandgap near 0.75 eV. The InGaAs can be employed to detect an output field 111 generated by upconverting an input field 110 with an energy down to 0.38 eV (up to about 3.4 μm in wavelength). By way of example and not limitation, the photodetector 101 can be a Ge photodetector. The Ge photodetector can similarly enable detection of an output

field 111 generated by upconverting an input field 110 with a wavelength above 3 μm .

By way of example and not limitation, the input field 110 can include two or more time-separated pulses. The input field 110 can be upconverted in the PC cavity 104 such that the PC cavity 104 acts as an optical autocorrelator. For example, two pulses can be collided at a time delay inside the PC cavity 104. The two pulses can be generated, for example, via a beam splitter from an input pulse source, such as a mode-locked laser. One half of the split beam can be directed through a delay line and then coupled into the PC cavity 104 via the incoupling element 105, and the other half can be coupled directly into the PC cavity 104 via the incoupling element 105. If the pulses are out of phase, upconversion will not necessarily occur in the PC cavity 104. If the pulses are in phase, the pulses can resonate together in a resonant mode of the PC cavity 104, and upconversion by second harmonic generation can occur. The intensity of the output field 111 can be measured and plotted as a function of delay between pulses. By observing where the output field 111 is enhanced as a function of delay, the duration of the pulses can be estimated.

By way of example and not limitation, a beam pump (not pictured) can be coupled to the incoupling element 105 (606). A pump field generated by the beam pump can be coupled into the PC cavity 104 via the incoupling element 105. In some embodiments, the pump field can be collinear with or combined with the input field 110. The pump field can couple into a first resonance mode of the PC cavity 104, and the input field 110 can couple into a second resonance mode of the PC cavity 104. The PC cavity 104 can be adapted to cause a parametric upconversion to thereby generate at least three output electromagnetic fields 111. The three output fields 111 can include the second harmonic of the pump field, the second harmonic of the input field 110, and the sum frequency generation of the input 110 and pump fields, where the sum frequency generation output field 111 can have a frequency equal to the sum of the frequencies of the pump field and the input field 110. The photodetector 101 can detect at least one of the output electromagnetic fields 111. This type of parametric upconversion can be referred to as three wave mixing. By way of example and not limitation, in some embodiments the output field 111 that has the second harmonic frequency of the pump field can be filtered out, for example by using a bandpass filter (not pictured).

Referring to FIG. 2, an exemplary device is similar to the device pictured in FIG. 1, except that a spacer layer 202 can be an asymmetric cladding covering the side of the PC cavity 104 proximate to the photodetector 101. By way of example and not limitation the asymmetric cladding can be a polymer cladding made of any suitable polymer, such as a polymer with a refractive index less than 1.8. The index of refraction of the asymmetric cladding can be less than the index of refraction of the PC cavity 104 and greater than the index of refraction of air. TIR can be weaker on the side of the PC cavity 104 covered by the asymmetric cladding than on the sides contacting air. In this way, the upconverted output field 111 can radiate toward the photodetector 101, thereby permitting detection of the output field 111 by the photodetector 101 through the spacer layer 202. Referring again to FIG. 1, when there is an air hole 103 between PC cavity 104 and photodetector 101, an equal amount of the output field 111 radiates away from the photodetector 101 as does towards the photodetector 101. Referring again to FIG. 2, because TIR is weaker on the side of the PC cavity 104 covered by the asymmetric cladding (i.e. spacer layer 202), more of the output field 111 radiates towards the photodetector 101 through the spacer layer 202 than away from the photodetector 101. Thus, efficiency can be enhanced because a greater amount of the output field 111 can reach the photodetector 101 through spacer layer 202.

Referring to FIG. 3, the device pictured in FIG. 3 is similar to the device pictured in FIG. 2, except that a bandpass filter 302 covers the sides of the PC cavity 104 not covered by the spacer layer 202. The bandpass filter 302 can allow certain wavelengths of electromagnetic radiation to pass through while blocking others. By way of example and not limitation, the input field 110 can be infrared light with a long wavelength and the output field 111 can be visible light with a shorter wavelength, e.g. green light. By way of example and not limitation, the bandpass filter 302 can be a longpass filter, meaning that it allows long wavelength (e.g. infrared) light to pass through while blocking shorter wavelength light (e.g. visible light, such as green light), thereby allowing the input field 110 to pass through while blocking the output field 111. By way of example and not limitation, the bandpass filter 302 can cover all sides of the PC cavity 104 except the side that faces the photodetector 101, such that the output field 111 cannot escape the PC cavity 104 except through the side that faces the photodetector 101. In such a way, efficiency can be enhanced because a greater amount of the output field 111 can reach the

photodetector 101 through the spacer layer 202 than if the bandpass filter 302 was not present in the device.

Referring to FIG. 4, the device pictured in FIG. 4 is similar to the device pictured in FIG. 2, except that the incoupling element 105 couples the input field 110 into the PC cavity 104 by evanescent coupling rather than end-to-end coupling or “butt coupling”. By way of example and not limitation, the incoupling element 105 can be a tapered fiber with a diameter smaller than 1.5 μm or a waveguide coupled with the PC cavity 104 in-plane. The input field 110 can be at least partially contained within the incoupling element 105. A portion of the input field 110 can exist outside of the incoupling element 105. The portion of the input field 110 that exists outside of the incoupling element 105 can be referred to as an evanescent field or evanescent tail. The evanescent field can overlap with the PC cavity 104, causing that portion of the input field 110 to transfer into the resonant mode of the PC cavity 104.

The foregoing merely illustrates the principles of the disclosed subject matter. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. For example, suitable materials different than those discussed above can be used for the various components. For example, different techniques can be used for fabricating and assembling the various components. It will thus be appreciated that those skilled in the art will be able to devise numerous techniques which, although not explicitly described herein, embody the principles of the disclosed subject matter and are thus within its spirit and scope.

CLAIMS

1. A detector for detecting at least one electromagnetic field, comprising:
a photodetector;
a photonic crystal cavity;
5 a spacer layer disposed between the photonic crystal cavity and the photodetector; and
an incoupling element adapted to couple at least one input electromagnetic field into the photonic crystal cavity,
wherein the photonic crystal cavity is adapted to upconvert the at least
10 one input electromagnetic field to form at least one output electromagnetic field, thereby permitting detection of the at least one output electromagnetic field by the photodetector through the spacer layer.
2. The detector of claim 1, wherein the photodetector is selected from the group consisting of a silicon (Si) photodetector, a Si avalanche photodiode (APD), an
15 indium gallium arsenide (InGaAs) photodetector, and a germanium (Ge) photodetector.
3. The detector of claim 1, wherein the spacer layer comprises a layer of low-index material.
4. The detector of claim 3, wherein the layer of low-index material
20 comprises a polymer layer.
5. The detector of claim 3, the spacer layer having at least one air hole disposed between at least a portion of the photonic crystal cavity and the photodetector, thereby enhancing a total internal reflection within the photonic crystal cavity at a boundary between the photonic crystal cavity and the at least one air hole.
- 25 6. The detector of claim 1, wherein the spacer layer comprises an asymmetric cladding at least partially covering at least one side of the photonic crystal cavity.
7. The detector of claim 6, wherein the asymmetric cladding comprises a polymer cladding.
- 30 8. The detector of claim 1, further comprising a longpass filter disposed on the photonic crystal opposite the photodetector.
9. The detector of claim 1, wherein the incoupling element is selected from the group consisting of a lens, a tapered fiber, and an in-plane waveguide.

10. The detector of claim 1, the photonic crystal cavity having at least one resonance mode, and wherein the incoupling element is adapted to couple the at least one input electromagnetic field into the at least one resonance mode of the photonic crystal cavity.

5 11. The detector of claim 1, wherein the photonic crystal cavity comprises a cavity having at least a first resonance mode and a second resonance mode, further comprising:

a beam pump coupled to the incoupling element,

10 wherein a pump field from the beam pump couples into the first resonance mode and the at least one input field couples into the second resonance mode, and

15 wherein the photonic crystal cavity is adapted to cause a parametric upconversion to thereby generate at least three output electromagnetic fields, thereby permitting detection of at least one of the output electromagnetic fields by the photodetector through the spacer layer.

12. A method for upconverting an input field, comprising:

receiving the input field;

coupling the received input field into a resonance mode of a photonic crystal cavity, thereby upconverting the input field to form an output field; and

20 radiating the output field through a spacer layer into a photodetector.

13. The method of claim 12, wherein the upconverting comprises second harmonic generation such that the output field has a wavelength that is approximately one half of a wavelength of the input field.

14. The method of claim 13, wherein the input field comprises a field
25 having a wavelength of approximately 1.5 μm .

15. The method of claim 12, wherein the input field comprises two or more time separated pulses, and wherein the input field is upconverted in the photonic crystal cavity such that the photonic crystal cavity acts as an optical autocorrelator.

16. A method for integrating a photonic crystal cavity onto a
30 photodetector, the method comprising:

fabricating a spacer layer on a first host chip;

transferring the spacer layer onto a photodetector;

fabricating a photonic crystal cavity on a second host chip;

transferring the photonic crystal cavity onto the spacer layer; and

adapting an incoupling element to couple at least one electromagnetic field into the photonic crystal cavity.

17. The method of claim 16, wherein the transferring the photonic crystal comprises transferring by elastomer stamping.

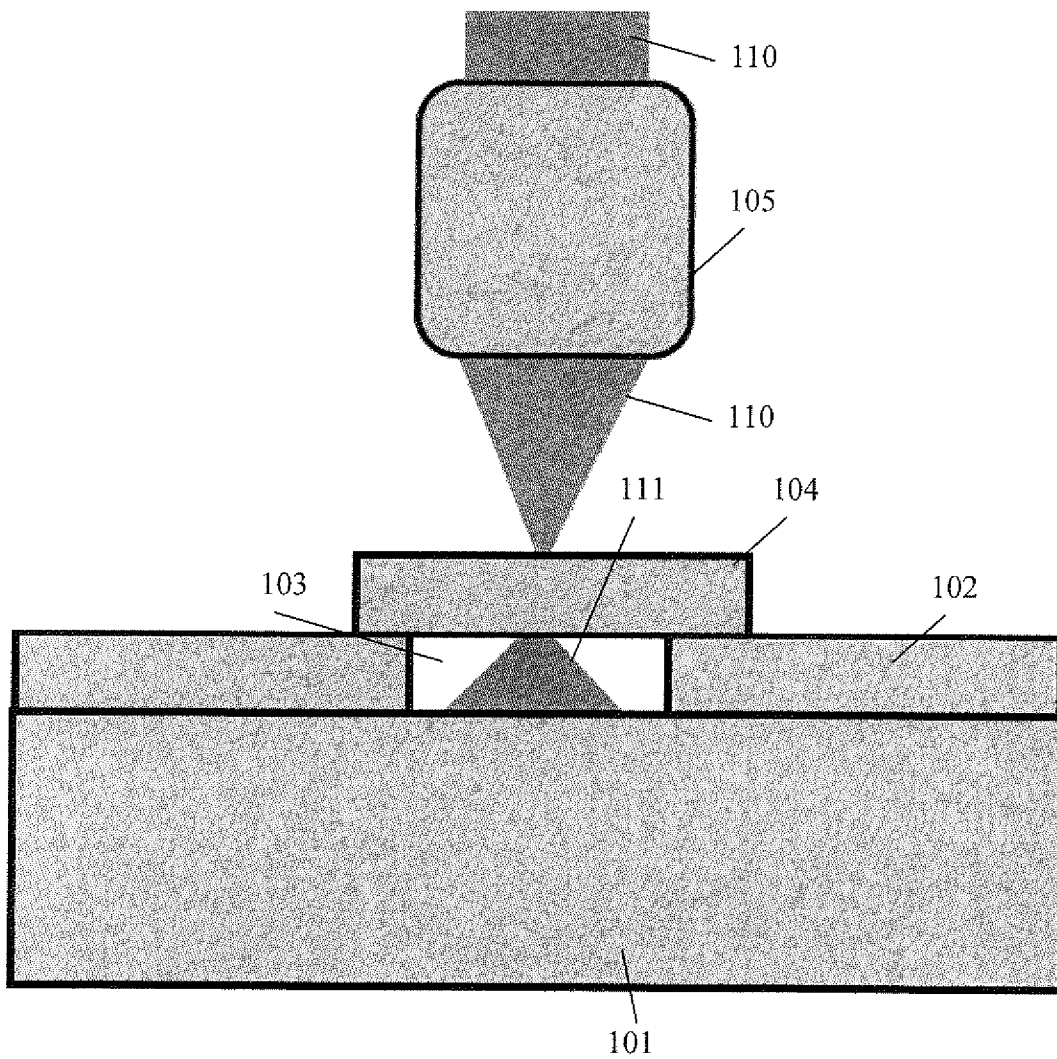
5 18. The method of claim 16, wherein the fabricating the spacer layer comprises fabricating an asymmetric cladding layer.

19. The method of claim 16, wherein the fabricating the spacer layer further comprises forming at least one air hole in the spacer layer.

10 20. The method of claim 16, further comprising coupling a beam pump to the incoupling element.

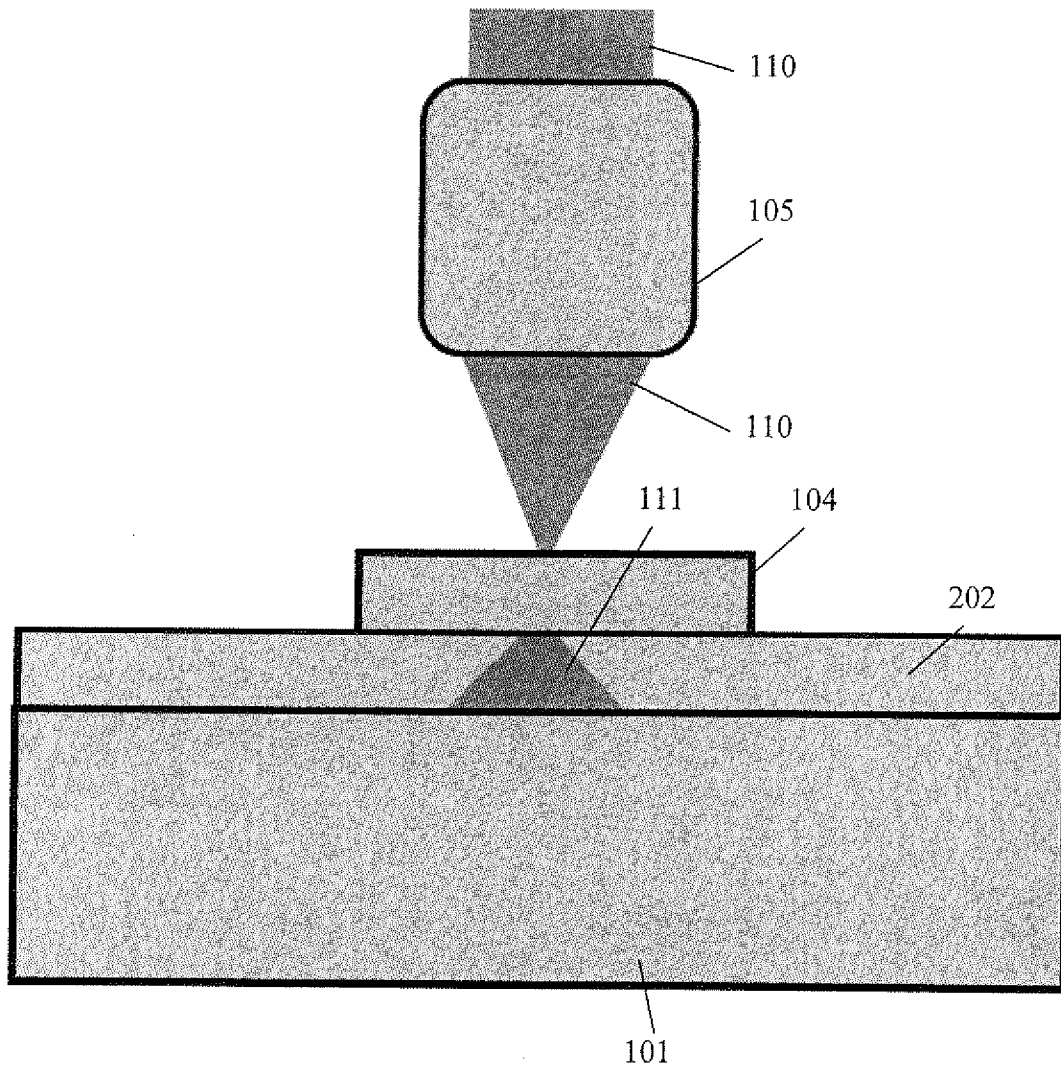
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FIG. 1



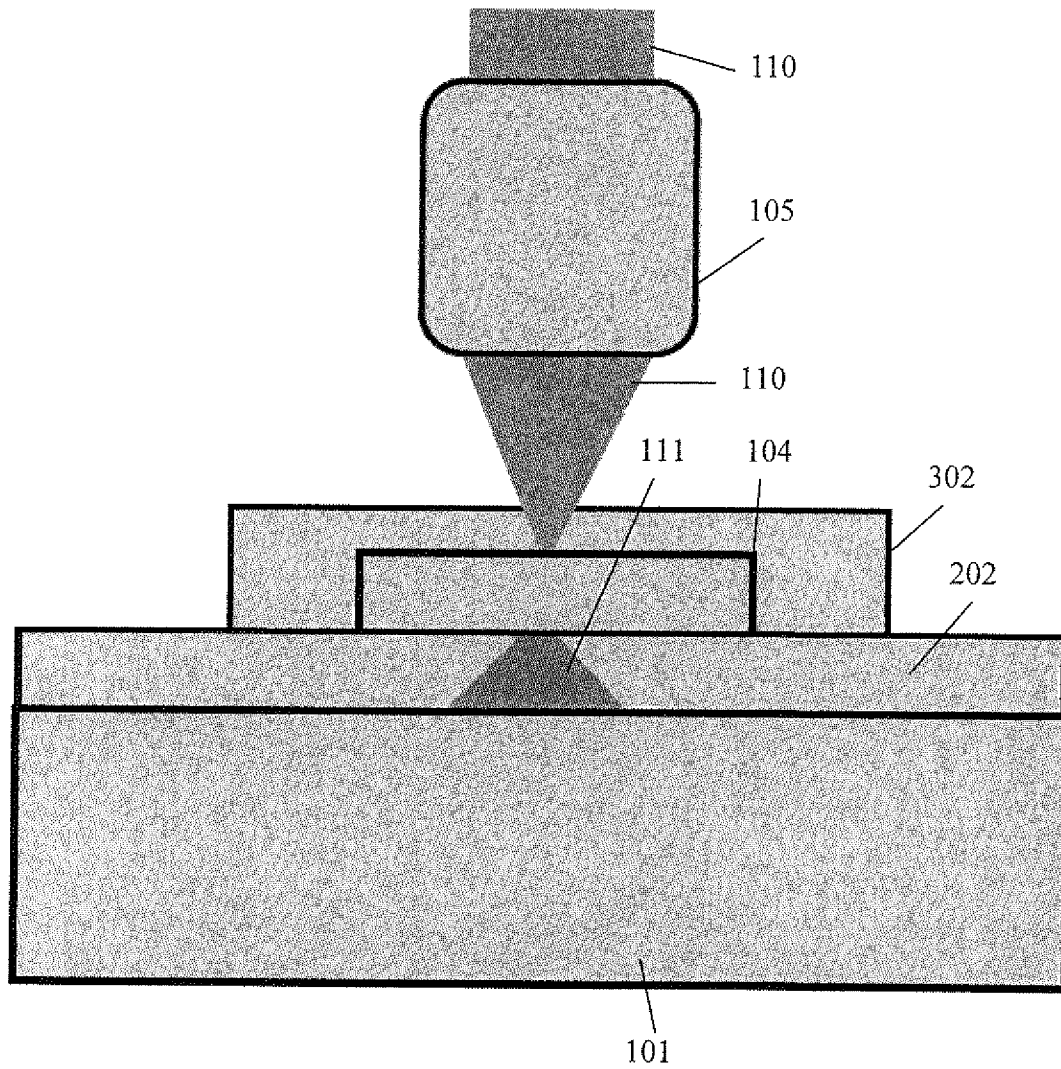
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FIG. 2



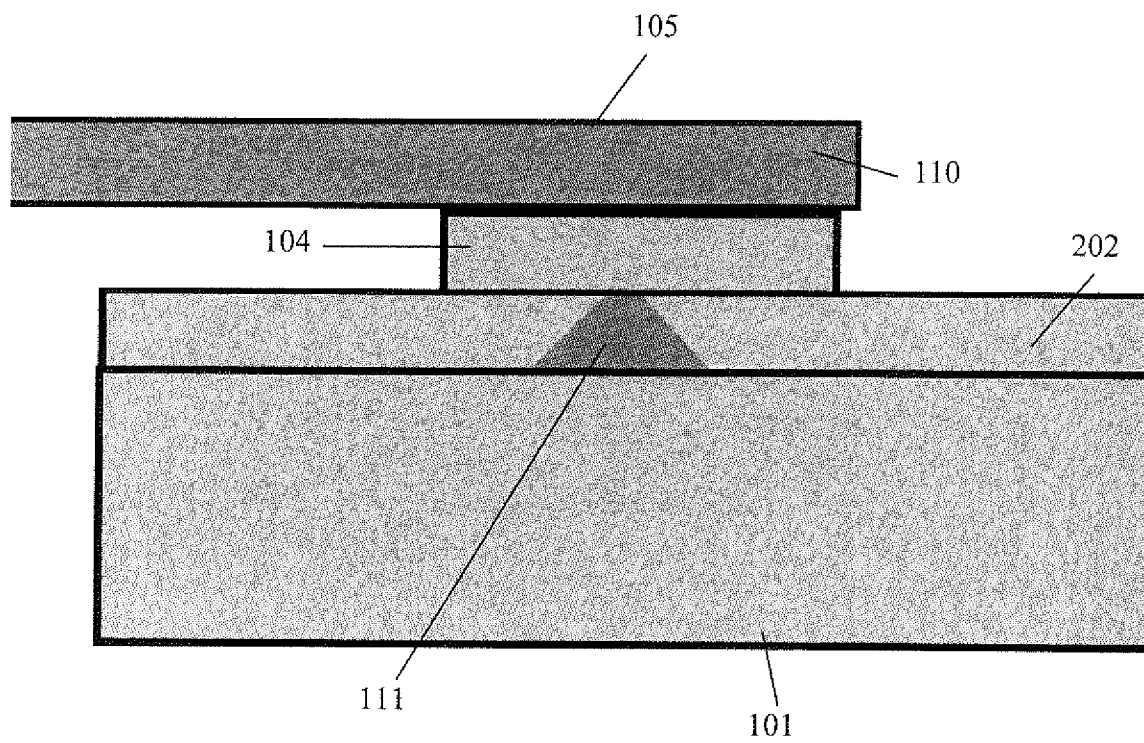
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FIG. 3



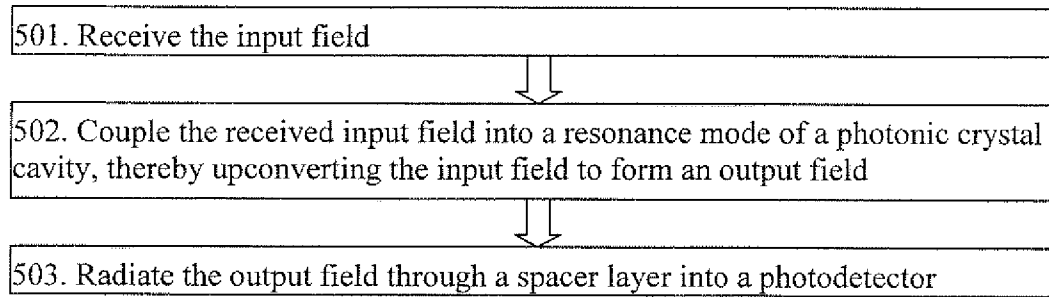
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FIG. 4



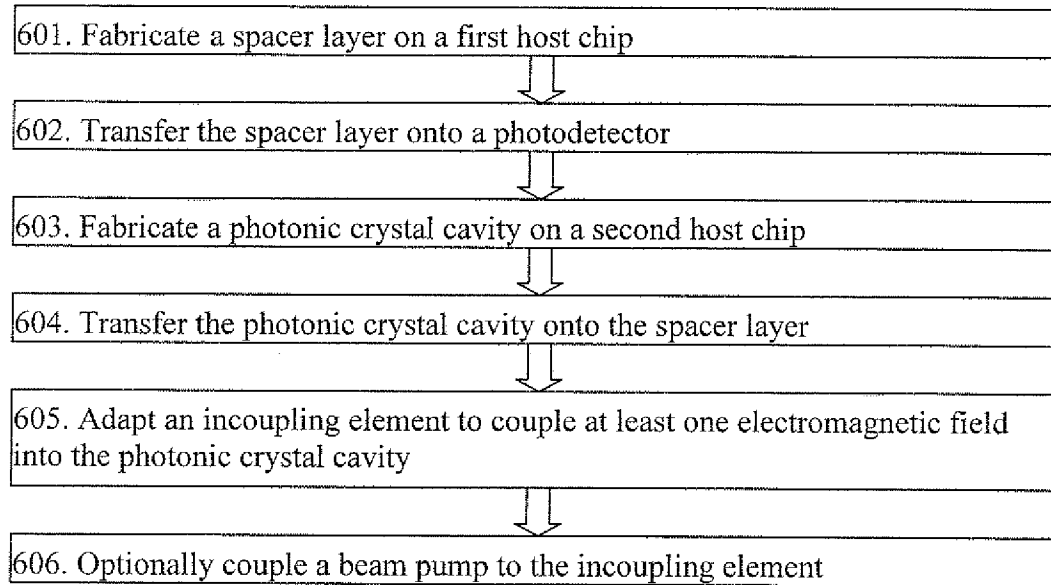
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FIG. 5



6/6

FIG. 6



INTERNATIONAL SEARCH REPORT

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PCT/US2013/031736

A. CLASSIFICATION OF SUBJECT MATTER

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USPC - 356/326

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

B. FIELDS SEARCHED

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

CPC - G01J 1/4214, 1/04, 1/42 (2013.01)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatBase, Orbit, Google Patents, ProQuest

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2011/046875 A1 (PERVEZ et al) 21 April 2011 (21.04.2011) entire document	12
Y		1-11, 13-20
Y	US 7,359,111 B1 (BRATKOVSKI) 15 April 2008 (15.04.2008) entire document	1-11, 13-15
Y	US 2007/0020144 A1 (DU et al) 25 January 2007 (25.01.2007) entire document	5, 19
Y	US 5,760,939 A (NAGARAJAN et al) 02 June 1998 (02.06.1998) entire document	6-7, 18
Y	US 2010/0014077 A1 (KHETANI et al) 21 January 2010 (21.01.2010) entire document	8
Y	WO 2011/089119 A1 (RIGNEAULT et al) 28 July 2011 (28.07.2011) entire document	11, 20
Y	US 2011/0151602 A1 (SPEIER) 23 June 2011 (23.06.2011) entire document	16-20
A	US 2012/0044489 A1 (CHAKRAVARTY et al) 23 February 2012 (23.02.2012) entire document	1-20
A	US 2005/0110992 A1 (SCHERER et al) 26 May 2005 (26.05.2005) entire document	1-20
A	US 2009/0237666 A1 (VOLLMER et al) 24 September 2009 (24.09.2009) entire document	1-20

☐ Further documents are listed in the continuation of Box C.

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"&" document member of the same patent family

Date of the actual completion of the international search

17 October 2013

Date of mailing of the international search report

29 OCT 2013

Name and mailing address of the ISA/US

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