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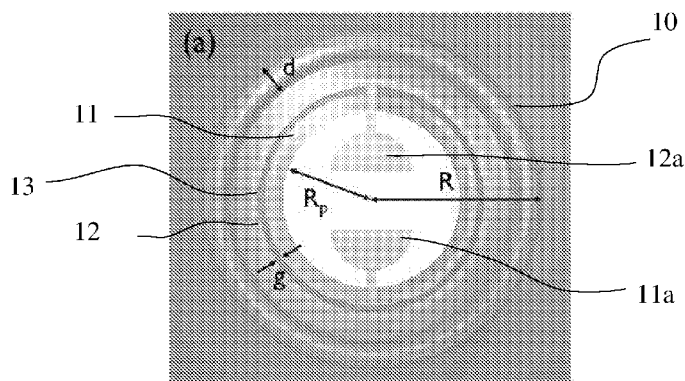


FIG 1

(57) Abstract: A tunable optical device comprising an optical ring cavity and one or more pairs of electrodes for capacitive actuation of the optical tuning. Applying a potential difference to the electrodes applies a capacitive force to the optical ring cavity which changes the optical resonance frequency. The device can be used as a binary optical switch.

TITLE

TUNABLE OPTICAL DEVICE

FIELD OF THE INVENTION

5 The present invention relates to the field of optical cavities. More particularly, the invention relates to a method and fabrication technique to tune the resonance frequencies of optical cavities.

BACKGROUND TO THE INVENTION

10 Optical cavities only interact with certain narrow, regularly spaced wavelengths of light called optical resonances. The ability to control ('tune') the wavelength of these resonances is important for a wide variety of applications. For example, a laser beam can only couple to a cavity if its wavelength precisely matches one of the resonances, and two distinct optical cavities cannot interact
15 with each other unless they share a common resonance wavelength. Important capabilities include the ability to tune fast, with high efficiency, and over a wide frequency range.

 For many optical cavities, and in particular for miniaturized cavities, the main currently used method to tune the resonance frequencies relies on thermal
20 heating, whereby heating the resonator changes its size and refractive index and therefore shifts the optical resonances. However, thermal tuning is relatively slow, has low efficiency and, depending on the material, can be only operable over a narrow range due to damage to the optical cavity caused by very high or very low temperatures.

25 Tunability is important for a particular class of optical cavities termed ring cavities. In some known prior art devices the optical field may be confined in whispering gallery modes (WGM) within a micron-scale disk fabricated on a chip. In our earlier published international patent application WO2015/039171 we describe a related device that uses an optical microcavity as the basis for an

optical magnetometer. Various optical cavities are described in WO2015/039171, the content of which is incorporated herein by reference.

The range of applications for tunable optical micro-cavities is quite broad, including biological, nanoparticle, and magnetic field sensing; on-chip precision clocks for GPS and other timing applications; and on-chip lasers, optical interconnects, and integrated optical delay lines for optical components in computation and communication. All of these applications are currently constrained by the lack of a fast, easy, efficient, and scalable way to tune the optical resonators; and typically rely instead on the tuneability of the laser sources themselves, which precludes the use of arrays of microresonators, and requires large and expensive laser sources which are not compatible with fully integrated solutions. Furthermore the emerging field of on-chip photonic circuitry will benefit from optical tuneability as well if networks of resonators are to be linked.

SUMMARY OF THE INVENTION

In one form, although it need not be the only or indeed the broadest form, the invention resides in a tunable optical device comprising:
an optical ring cavity having at least an optical resonance frequency; and
electrodes forming a capacitor;
wherein applying a potential difference between the electrodes generates a capacitive force applied to the optical ring cavity that shifts the optical resonance frequency.

The optical ring cavity is suitably a circular or elliptical cavity where the light circulates by grazing incidence total internal reflection around the perimeter of the cavity. The optical ring cavity may be a microdisk with a diameter in the range of a few micrometers to a few centimetres. Preferred dimensions are a diameter from about 5 microns to about 30 millimetres, but more preferably a diameter in the range of about 60 micron to about 16 millimetres.

Alternatively, the optical ring cavity may be a rectangular resonator, preferably square, where light circulates by reflection from dielectric coatings on the surface of the resonator.

5 The electrodes may be selected from gold, aluminium, indium tin oxide, or other materials demonstrating conductive properties.

There may be a single pair of electrodes or a plurality of pairs of electrodes. The electrodes may be designed for large capacitance by coating with a high dielectric material. In the case of multiple pairs of electrodes they may be inter-digitated. By inter-digitated it is meant that the multiple electrodes
10 are arranged in an array of alternating polarity.

The electrodes may be deposited onto the optical cavity. Preferably the electrodes are deposited adjacent or in a slot formed in the optical cavity. The slot may be filled with air or a material with a higher dielectric constant.

15 In a yet further form the invention resides in a method of fabricating an optical ring cavity with capacitive tuning including the steps of:
forming an optical ring cavity;
locating electrodes on the optical ring cavity to form a capacitor; and
heating the cavity to reflow, and therefore smooth, its surface, without damaging the electrodes.

20 The dielectric of the capacitor may be formed in the material of the optical ring cavity by injecting ions into the surface of the material, by removing or replacing material of the optical ring cavity or by forming the optical ring cavity from a composite material. The dielectric of the capacitor may suitably be air.

25 The optical ring cavity structure may be formed by one or more of:
photolithography; focussed ion beam milling; electron beam lithography;
diamond turning; laser ablation, or drilling.

The electrodes may be formed by one or more of: physical vapour deposition; sputtering; chemical vapour deposition; pulsed laser deposition; metal organic molecular beam deposition; or spray pyrolysis.

In a yet further form the invention may reside in a fabrication technique to reflow an optical ring cavity structure with electrodes comprising:

under-etching the optical ring cavity in two stages;

stopping the first under-etching stage before the material underneath the

5 electrodes is etched away;

applying heating with a CO₂ laser to melt the material of the optical ring cavity

after the first under-etching stage, with the thermal conductivity of the material

remaining underneath the electrodes preventing electrode heating and damage;

under-etching the optical ring cavity in a second stage to free the outer part of

10 the cavity from the material underneath it and allow it to contract and expand upon application of a capacitive force.

Further features and advantages of the present invention will become apparent from the following detailed description.

15

BRIEF DESCRIPTION OF THE DRAWINGS

To assist in understanding the invention and to enable a person skilled in the art to put the invention into practical effect, preferred embodiments of the invention will be described by way of example only with reference to the accompanying drawings, in which:

20

FIG 1 shows a first embodiment of a tunable optical device;

FIG 2 shows an FEM simulation of the electro-magnetic energy distribution in the tunable optical device of FIG 1;

FIG 3 shows an FEM simulation of the radial breathing mode-like mechanical mode in the tunable optical device of FIG 1;

25

FIG 4 shows an optical microscope side view of the tunable optical device of FIG 1;

FIG 5 is a sketch of a top view of the tunable optical device of FIG 1;

FIG 6 is a schematic demonstrating capacitive resonance tuning of the tunable optical device of FIG 1;

FIG 7 shows the experimentally observed optical resonance;

FIG 8 shows the frequency tuning as a function of applied bias voltage;

FIG 9 shows a second embodiment of a tunable optical device;

5 FIG 10 shows a simulation of the electric field from the electrodes of the tunable optical device of FIG 9;

FIG 11 is a plot of total capacitance as a function of electrode gap for the arrangement of FIG 10;

FIG 12 is a plot of force per volt as a function of electrode gap for the arrangement of FIG 10;

10 FIG 13 shows a simulation of the electromagnetic energy density around the electrodes of the tunable optical device of FIG 9 with various dielectric coatings;

FIG 14 is a plot of total capacitance as a function of electrode gap for the arrangement of FIG 13;

15 FIG 15 is a plot of force per volt as a function of electrode gap for the arrangement of FIG 13;

FIG 16 displays a variety of pedestal designs;

FIG 17 shows a third embodiment of a tunable optical device;

FIG 18 shows a fourth embodiment of a tunable optical device; and

FIG 19 shows a possible fabrication process for a tunable optical device

20

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention reside primarily in a method and fabrication technique to tune the resonance frequencies of optical cavities.

25 Accordingly, the elements have been illustrated in concise schematic form in the drawings, showing only those specific details that are necessary for understanding the embodiments of the present invention, but so as not to obscure the disclosure with excessive detail that will be readily apparent to those of ordinary skill in the art having the benefit of the present description.

In this specification, adjectives such as first and second, left and right, and the like may be used solely to distinguish one element or action from another element or action without necessarily requiring or implying any actual such relationship or order. Words such as “comprises” or “includes” are intended to
5 define a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed, including elements that are inherent to such a process, method, article, or apparatus.

Referring to FIG 1 there is shown a top view of a first embodiment of an
10 optical ring cavity 10 with capacitive electrodes 11, 12 used to provide the capacity for voltage tuning of its optical resonance frequencies. The device comprises an optical ring cavity having a circular slot 13 fabricated in it and electrodes 11, 12 deposited on either side of the slot 13. The optical ring cavity is a toroid, but the invention is not limited to this shape.

15 By ring cavity is meant that the cavity has a configuration in which optical radiation circulates unidirectionally. Most commonly the ring cavity will be circular or elliptical but may also be rectangular, triangular, or some other shape that permits optical radiation to circulate within the cavity and for the radiation to be coupled in and out at the same, or about the same, position.

20 The relevant dimensions shown in FIG 1 are the toroid major radius **R**, toroid minor diameter **d**, electrode gap **g** and undercut silicon pedestal radius **R_p**. Electrical connection to inner electrode 11 is provided by tab 11a and electrical connection to outer electrode 12 is provided by tab 12a.

25 By way of example only, the optical cavity may be a microdisk with a diameter in the range of a few micrometers to a few centimetres. The inventors have found that suitable dimensions are a diameter from about 5 microns to about 30 millimetres, but speculate that a diameter in the range of about 10 micron to about 0.5 millimetres is most suitable.

30 FIG 2 shows a simulation of one optical whispering gallery mode within the device. It is a FEM (Finite Element Method) simulation of a ($p=1$, $m=280$) WGM at 1550 nm, showing the electro-magnetic energy density in log scale. The

black scale bar corresponds to 8 microns. FIG 3 shows a simulation of a mechanical eigenmode of motion of the device which couples efficiently to the capacitive actuation. It shows an FEM model of the radial breathing mode-like mechanical mode at 18 MHz. As can be seen from FIG 2 and FIG 3, an attractive force generated between the electrodes 11, 12 will affect the radial breathing mode and thus change the optical resonance. This effect can be used for resonantly enhanced tuning.

The structure of the tunable optical microcavity is shown in FIG 4. FIG 4 is an optical microscope side-view of a fabricated device. This image was obtained by combining 10 individual images taken at different focus to overcome the shallow depth of field (focus stacking). The optical microcavity 10 has a slot 13 cut into it but leaving a bridge to join the outer ring with the central pedestal. The device may be formed on a silicon wafer using a similar process to the process described in WO2015/039171.

To better assist with understanding the structure of the tunable optical cavity a simple sketch is provided as FIG 5. A silica disc comprising a slot 51 is fabricated, so that after under-etching a portion of the underlying material, an air gap is formed between a central portion 52 and an outer portion 53 (where the whispering gallery mode resonances are localized). The central portion 52 rests upon a pedestal (not shown). An anchor 54 is left in place to support the outer portion 53. As shown in FIG 1, electrodes are fashioned either side of the air gap to form a capacitor. When a potential difference is applied across the electrodes opposite charges accumulate on the electrodes and generate an attractive force, thus applying strain to the outer portion 53 and changing the optical resonance of the whispering gallery mode.

As will be understood by persons skilled in the art, a capacitor may be formed with a variety of conductive materials. In similar manner the slot may be filled with a dielectric material to increase the capacitive force generated. This is explained in more detail below. It will also be clear that the invention is not limited to a disc but may be applied to other optical cavities, such as those shown in WO2015/039171.

The capacitive force (F) generated may be calculated using:

$$F = \frac{1}{2} \frac{dC(x)}{dx} V^2 \quad (1)$$

where $C(x)$ is the position dependent capacitance formed by the two capacitor plates. It will be noted that F scales with the square of the applied voltage. It will also be appreciated that the capacitance will increase as the distance between the plates decreases and as the length of the plates increases. Thus a greater capacitive force can be applied if larger electrodes can be used and/or the spacing between the electrodes is made as small as possible.

In one embodiment (not shown) a capacitor may be separately formed to fit in the slot 51. The capacitor may have relatively large plates that extend above and below the limits of the slot and may have a preferred dielectric material. The capacitor is bonded into the slot as part of the fabrication process for the tunable optical cavity.

The optical resonance frequencies of the optical cavity 10 are tuned by applying a bias voltage between the electrodes 11, 12. This applies a capacitive force to the structure of the device, deforming it. Since the optical resonance frequencies depend on the size and refractive index of the device, and the deformation alters these properties, the bias voltage results in a change in the optical resonance frequencies of the device. The magnitude of the change in optical resonance frequencies depends on the level of applied voltage, the material properties of the device, and the capacitance between the electrodes. The material properties of the device and the capacitance between the electrodes may both be optimised in a variety of ways to maximize the frequency shift. For instance, by using inter-digitated electrodes, or coating the electrodes with a high dielectric constant material, as described below.

Referring to FIG 6 there is shown a schematic of an experiment used to verify the optical resonance frequency shift generated by an applied bias voltage. A tunable laser 60 generates a laser beam that is coupled to an optical fibre 61. Any tunable laser may be chosen that generates an output at an appropriate frequency for the optical resonances of the optical cavity. The output 62 of the laser is evanescently coupled into the optical cavity 63 via a tapered

section 64 of the optical fibre. FPC is a fibre polarization controller. Optical radiation is coupled out of the optical cavity in the same manner. The tapered portion of the optical fibre abuts the optical cavity. Light exiting the optical fibre is detected by a photodiode 65, or other suitable photodetector. Scanning the frequency of the laser allows optical resonances to be located via the absorption they introduce to the optical field as shown experimentally in FIG 7. Applying a bias voltage 66 to the electrodes shifts the resonance frequencies. These shifts may be tracked by tracking the laser frequency with maximum optical absorption. The frequency shift as a function of bias voltage is displayed experimentally in FIG 8. It can be seen that, in this implementation, an optical frequency shift of around 4.5 kHz per volt-squared is achieved, verifying that the capacitive tuning technique works.

By way of example, with a 200 V DC bias, a 5V peak to peak (V_{pp}) AC modulation is sufficient to provide full depth (on/off) modulation for this embodiment. The voltage requirement is further reduced by a factor Qm if the AC drive is resonant with a mechanical mode of quality factor Qm . In deed for an AC drive resonant with, say, an 18 MHz mechanical mode (with $Qm = 180$), only 30 mV $_{pp}$ is required for full depth modulation. This very low voltage optical modulation makes the capacitively driven microtoroids of the invention efficient radio frequency to optical conversion devices.

The experimental arrangement of FIG 6 shows that the tunable optical cavity 63 can be used as a switch for transmission of the output of the 1550nm laser 60. That is to say, when the DC bias voltage is not applied a signal will be received at the photodiode 65. When the DC bias voltage is applied the photodiode 65 will not show a signal (the device can also be configured for the converse). This is a binary optical switch. Persons skilled in the art will appreciate how an array of such switches can be configured for optical communication and other applications.

As mentioned above, the tuning range can be extended by increasing the capacitive force. One approach to achieve this is to use a plurality of electrode pairs. Referring to FIG 9, there is shown a possible design for inter-digitated electrodes to improve the frequency shift obtained for a fixed applied bias

voltage. The electric field amplitude generated by the bias voltage in this configuration is shown in FIG 10. FIG 10 shows a cross-sectional view through the line 90 in FIG 9. The multiple electrode pairs apply a larger force to the optical cavity thus causing a greater deformation and hence producing a greater tuning range.

Also as mentioned above the capacitive force increases as the gap between the electrodes is reduced. FIG 11 shows the capacitance as a function of electrode gap for a single electrode pair (as shown in FIG 1) and for 5, 10 and 15 pairs having a configuration similar to FIG 9. FIG 11 shows that the total capacitance increases with the number of inter-digitated electrode pairs. The bottom line is a single electrode pair and the next lines are, in order, 5, 10 and 15 electrode pairs.

FIG 12 shows the force per volt applied to the structure as a function of electrode gap for a single electrode pair (as shown in FIG 1) and for 5, 10 and 15 pairs having a configuration similar to FIG 9. FIG 12 shows that the applied force increases with the number of inter-digitated electrode pairs.

By way of example, the design shown in FIG 9 consists of 30 electrodes (15 electrode pairs) each of width 0.9 micron and separation of 150 nm patterned on the top surface of the microtoroid resonator. The capacitance calculated for this structure is 250 fF, which is more than 50 times larger than the design shown in FIG 1.

Persons skilled in the art will understand that the invention is not limited to 1, 5, 10 or 15 pairs of electrodes but could be constructed with 2, 3, 4, 6, 7, 8, 9, 11, 12, 13, 14, 16 or more pairs of electrodes.

Referring to FIG 13, there is shown an enhancement in capacitance and force applied to the structure of the device using several possible high dielectric coatings over the electrodes, including SiO₂, TiO₂, and BST (Ba_{0.7} Sr_{0.3}TiO₃ in a silica suspension). FIG 14 and FIG 15 show data similar to FIG 11 and FIG 12. In each case the bottom trace is the result for an air gap and is the same data as shown in FIG 11 and FIG 12. The other traces are, from bottom to top, SiO₂, TiO₂, and BST. A simulation of the electromagnetic energy density for each of

the coatings are shown, respectively, from left to right in FIG 13.

In the embodiments described above the optical cavity is formed on a silicon wafer and supported by a central silicon pedestal. The optical cavity is supported by an anchor, as shown in FIG 5. FIG 16(a) shows the simulated mechanical compliance for the single anchor configuration of FIG 5. FIG 16(b) shows the simulated mechanical compliance for a double anchor configuration with the anchors opposite and coaxial. FIG 16(c) shows the simulated mechanical compliance for a four anchor configuration with the anchors in a cross configuration. The simulated mechanical compliance for a “no slot” configuration is shown in FIG 16(d) for comparison. It is clear that the number of anchors impacts the mechanical compliance and therefore the ability to tune the optical cavity. The inventors speculate that the width of the anchor will also have an effect. Various embodiments of the invention may have 1, 2, 3, 4 or more anchors.

In the embodiment described in FIG 9, the slot is removed, so as to be able to position the electrodes closer to one another, to be able to combine multiple inter-digitated electrodes and to be able deposit a dielectric coating over the electrodes. All of these contribute to strongly increase the device capacitance and force per applied volt, at the cost of a somewhat reduced mechanical compliance.

Although the preferred embodiment has been described in terms of a microdisk optical cavity the invention is not limited to a particular configuration. A “racetrack” configuration is shown in FIG 17. This optical resonator 170 may be fabricated on a silica wafer by, for example, femtosecond laser pulses in order to define a region of modified refractive index within the material, or a wet etch step with, for example, hydrofluoric acid or a reactive ion etching step in order to define the resonator boundaries of a waveguide. Planar electrodes, such as inter-digitated electrodes 171 are patterned over all, or a portion of, the cavity and may be covered with a high K dielectric coating (not shown) as described previously. The electrodes allow for strain tuning of the resonances by changing the length of the “racetrack”.

Referring to FIG 18, there is shown a circular or elliptic cavity 180 fabricated by, for example, a combination of selective or non selective chemical wet etches and/or dry reactive ion etching steps. The cavity can be fabricated out of a dielectric material (such as for example reflowed or non reflowed silica, chalcogenide and silicon nitride), or a semiconductor material such as Silicon, Gallium Arsenide, Aluminum Nitride, Silicon Carbide or Indium Phosphide. A planar inter-digitated capacitance 181 is patterned over all, or a portion of, the cavity, while avoiding the periphery where the optical mode is localized by total internal refraction. The cavity itself can be undercut in order to increase mechanical compliance, or can remain entirely bound to the substrate. The electrodes may or may not be embedded and may be covered with a high K dielectric coating (not shown), and allow for tuning of the resonances.

In order to fabricate a tunable optical device according to the embodiment of FIG 1 the technique outlined in FIG 19 may be followed. The optical cavity is fabricated using a combination of conventional photolithographic processes and a wet hydrofluoric acid based etch (Steps 1-3). Next, the electrodes are patterned on the cavity using conventional photolithographic processes, metal deposition and lift off (Steps 4-6). A third lithography step is required to cover the slotted portion of the cavity, in order to avoid unwanted etching of the device during the first of the two following underetch stages (Step 7). The optical resonator is under-etched in two stages. The first under-etching stage is stopped before the material underneath the electrodes is etched away (Step 8) and heat is applied with a CO₂ laser to melt (reflow) the material of the optical cavity, enabling greatly enhanced optical properties (Step 9). The thermal conductivity of the material underneath the electrodes prevents the electrodes from heating and damage. The second under-etching stage frees the reflowed outer part of the resonator from the material underneath so it can contract and expand upon application of a capacitive force (Step 10).

This invention proposes the use of capacitive forces to achieve tuning of an optical cavity. The use of capacitive force provides wide tuning range, high efficiency, and fast tuning. When a bias voltage is applied across two electrodes, the capacitive force between the electrodes compresses or extends the size of

the device, shifting the frequencies of the optical resonances. The tunable optical device will find many applications including biological, nanoparticle, and magnetic field sensing; efficient radio to optical frequency conversion, optical routing and switching; on-chip precision clocks for GPS and other timing applications; and on-chip lasers, optical interconnects, and integrated optical delay lines for optical components in computation and communication.

The ability to produce very small devices on the micron scale permits a large number of devices to be produced on a single silicon wafer. By way of example, an array of 1000 by 1000 tunable optical cavities with a diameter of about 60 μm micron will fit on a single wafer of size 100mm square (allowing for about 40 μm spacing between cavities). Semiconductor lasers may also be fabricated along the edges of the wafer and optical waveguides formed in the wafer from the lasers to the optical cavities. It will be understood that this produces 1000000 addressed optical devices.

CLAIMS

1. A tunable optical device comprising:
an optical ring cavity having at least an optical resonance frequency; and
electrodes forming a capacitor;
5 wherein applying a potential difference between the electrodes generates a
capacitive force applied to the optical ring cavity that shifts the optical resonance
frequency.
2. The tunable optical device of claim 1 wherein the electrodes are
deposited onto the optical ring cavity or are deposited adjacent or in a slot
10 formed in the optical ring cavity.
3. The tunable optical device of claim 1 wherein the optical ring cavity is
selected from one of: a circular cavity; an elliptical cavity; a rectangular cavity; a
square cavity.
4. The tunable optical device of claim 3 wherein the optical ring cavity has a
15 largest dimension in the range of: about 5 microns to about 30 millimetres; or
about 10 micron to about 0.5 millimetres; or about 60 micron to about 16
millimetres.
5. The tunable optical device of claim 1 wherein the electrodes are selected
from: gold; aluminium; or indium tin oxide.
- 20 6. The tunable optical device of claim 1 comprising a single pair of
electrodes.
7. The tunable optical device of claim 1 comprising a plurality of pairs of
electrodes.
8. The tunable optical device of claim 7 comprising 5 pairs of electrodes or
25 10 pairs of electrodes or 15 pairs of electrodes.
9. The tunable optical device of claim 7 wherein the pairs of electrodes are
interdigitated.
10. The tunable optical device of claim 1 wherein the electrodes are
deposited on a surface of the optical ring cavity.

11. The tunable optical device of claim 1 further comprising a slot formed in the optical ring cavity and wherein the electrodes are deposited adjacent or in the slot.

12. The tunable optical device of claim 11 wherein the electrodes are deposited in the slot and extend beyond the extent of the slot.

13. The tunable optical device of claim 11 comprising a single anchor across the slot.

14. The tunable optical device of claim 11 comprising two anchors across the slot.

15. The tunable optical device of claim 11 comprising three or more anchors across the slot

16. The tunable optical device of claim 1 wherein the optical ring cavity is fabricated as a region of modified refractive index forming a waveguide.

17. The tunable optical device of claim 1 further comprising a power supply applying an AC potential difference with a DC bias to the electrodes.

18. The tunable optical device of claim 17 wherein the DC offset is about 200 V and the AC is about 5 Vpp.

19. A method of fabricating an optical device with capacitive tuning including the steps of:

forming an optical ring cavity;
locating electrodes on the optical ring cavity to form a capacitor; and
heating the optical ring cavity to reflow, and therefore smooth, its surface, without damaging the electrodes.

20. In a yet further form the invention may reside in a fabrication technique to reflow an optical ring cavity structure with electrodes comprising:

under-etching the optical ring cavity in two stages;
stopping the first under-etching stage before the material underneath the electrodes is etched away;
applying heating with a CO₂ laser to melt the material of the optical ring cavity after the first under-etching stage, with the thermal conductivity of the material

underneath the electrodes preventing electrode heating and damage;
under-etching the optical ring cavity in a second stage to free the outer part of the cavity from the material underneath it and allow it to expand upon application of a capacitive force.

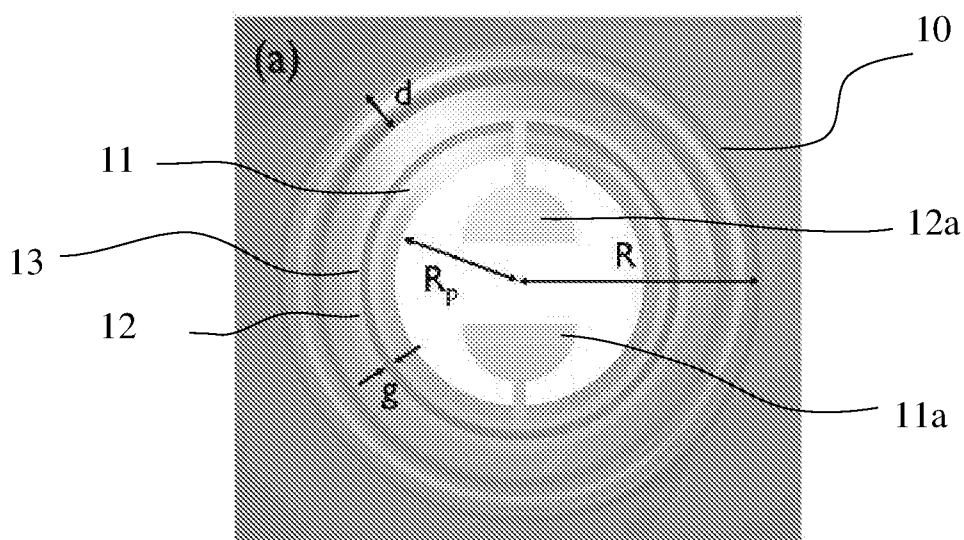


FIG 1

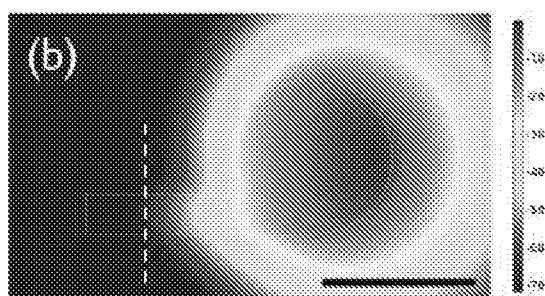


FIG 2

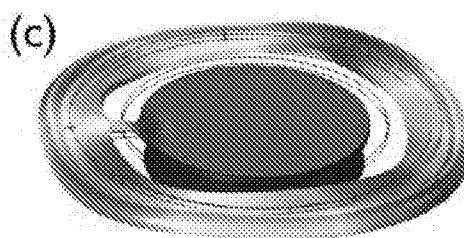


FIG 3

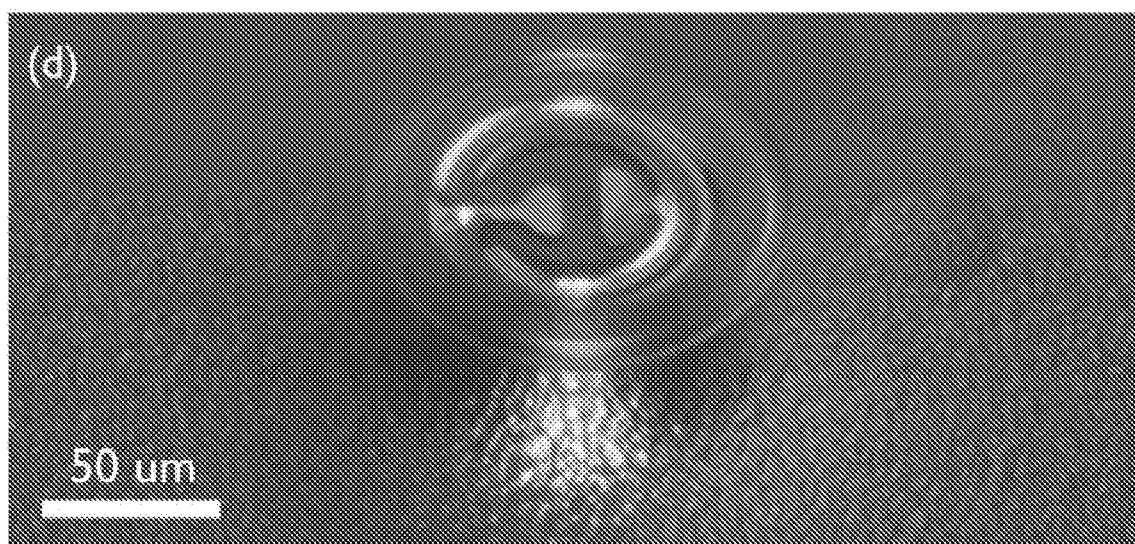


FIG 4

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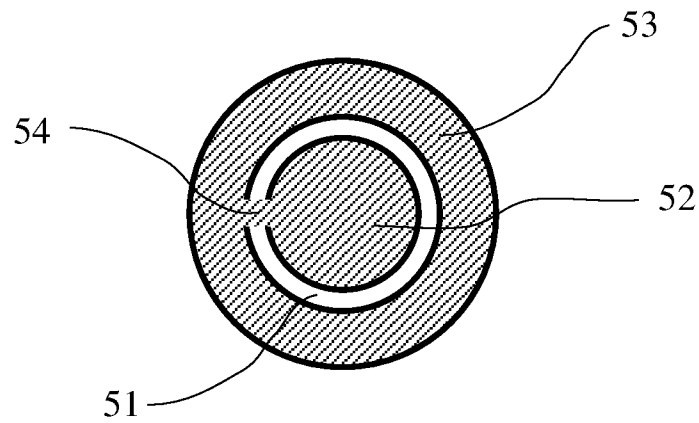


FIG 5

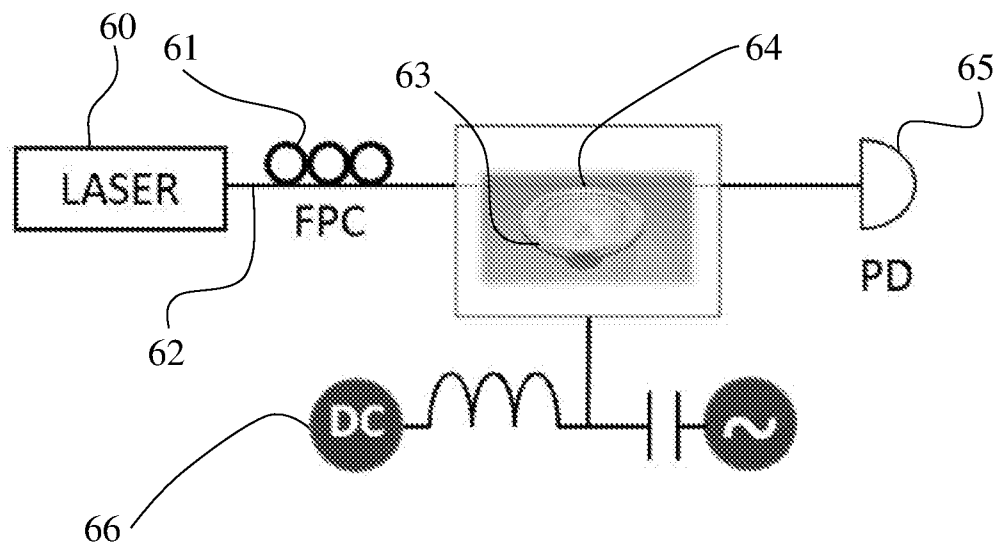


FIG 6

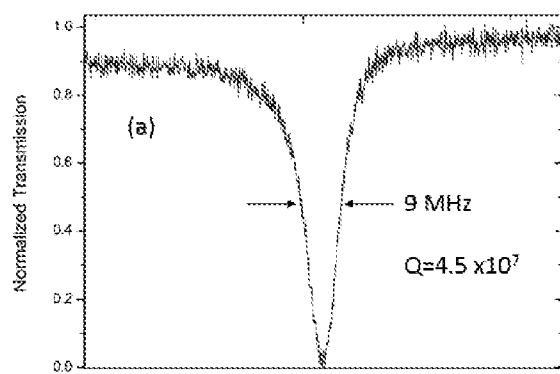


FIG 7

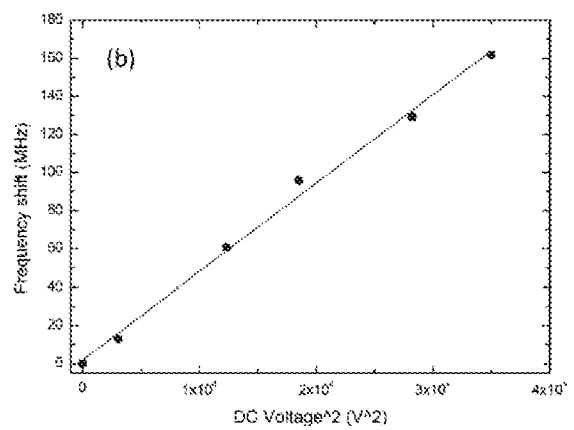


FIG 8

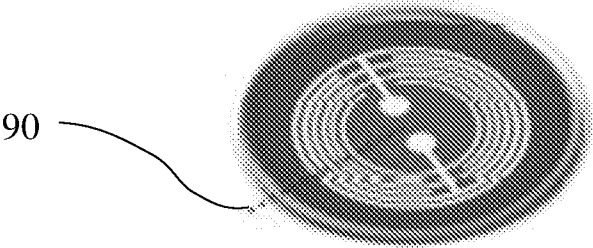


FIG 9

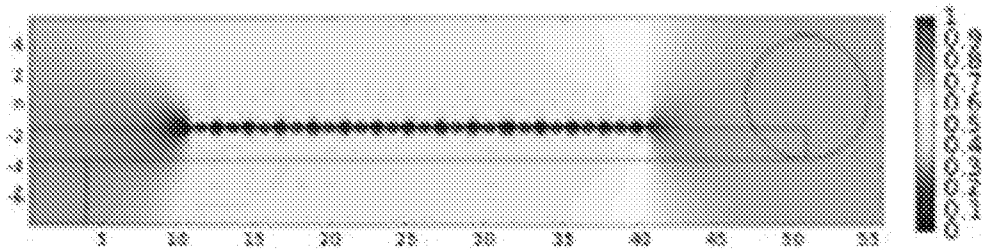


FIG 10

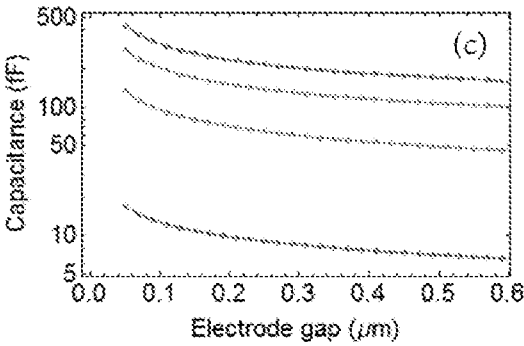


FIG 11

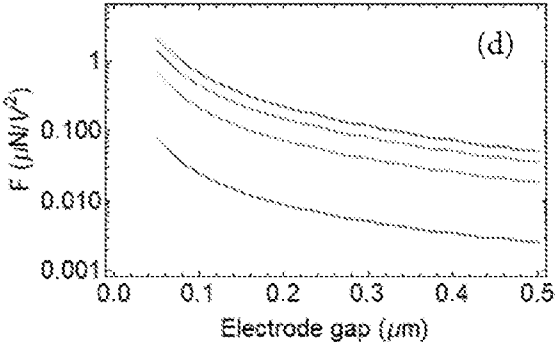


FIG 12

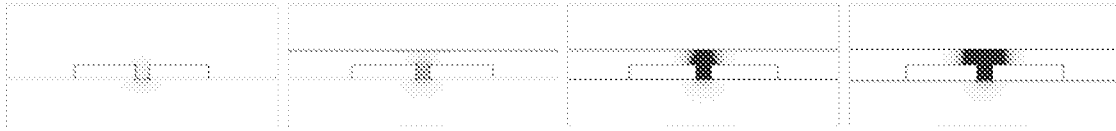


FIG 13

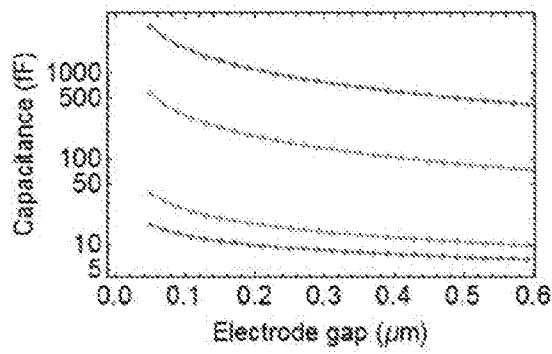


FIG 14

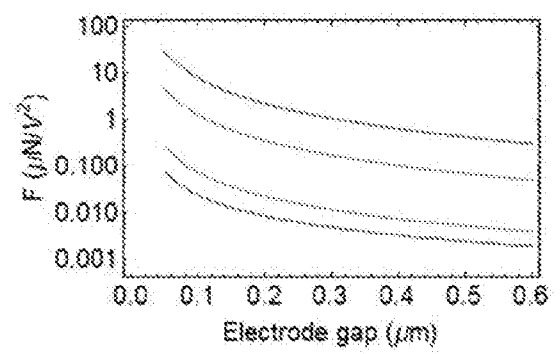


FIG 15

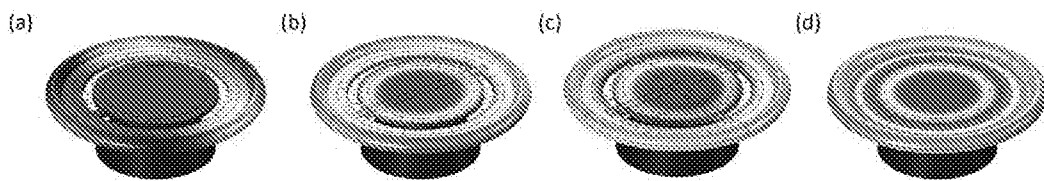


FIG 16

5/5

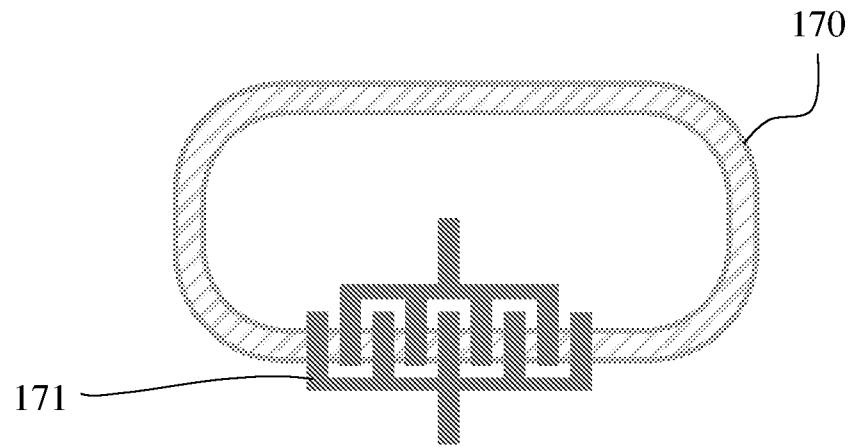


FIG 17

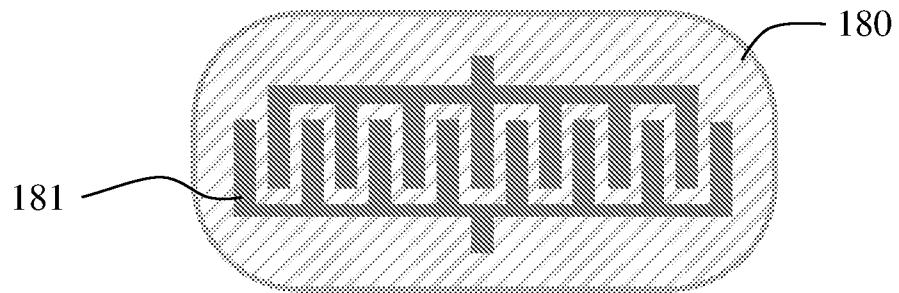


FIG 18

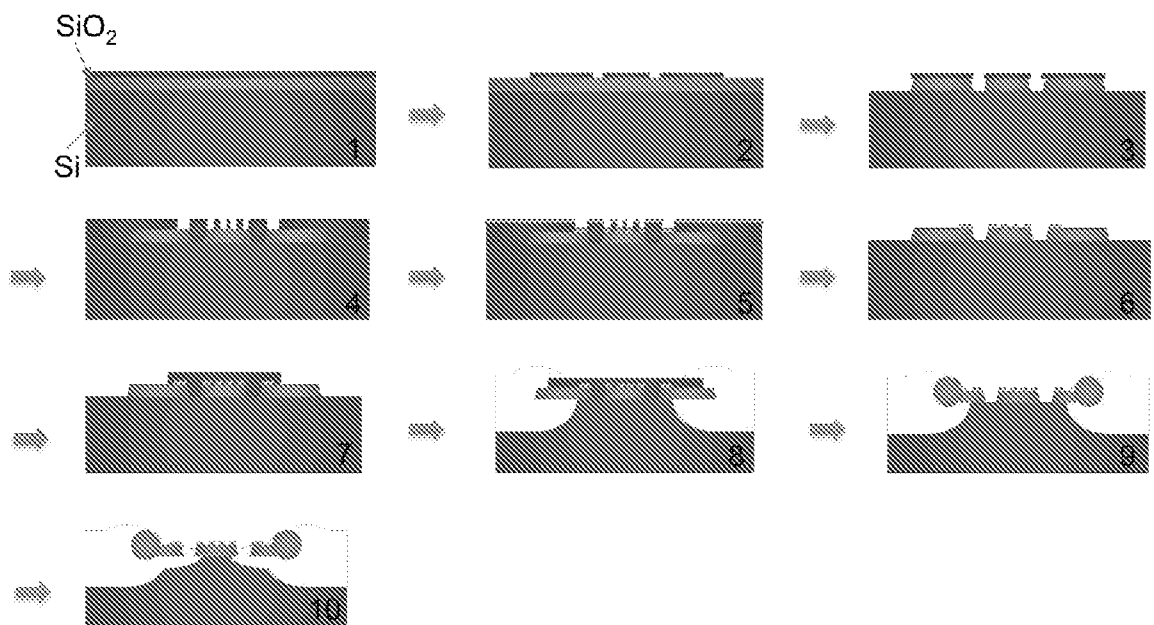


FIG 19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2016/050644

A. CLASSIFICATION OF SUBJECT MATTER

G02B 6/293 (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)

Applicant(s)/Inventor(s) name searched in internal databases provided by IP Australia

WPIAP, EPODOC: IPC, CPC G02F1, G02B6, G02B26 & Keywords (capacitive, frequency, wavelength, select, tune, cavity, resonate, ring, disc, torus) and like terms; Applicant/Inventor Search

Google Patents/Scholar: ring, resonator, capacitive, force, tuning, interdigitated, electrodes and like 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

* "A"	Special categories of cited documents: 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 23 September 2016	Date of mailing of the international search report 23 September 2016
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au	Authorised officer Andrew Walker AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262223676

INTERNATIONAL SEARCH REPORT C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		International application No. PCT/AU2016/050644
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 8849075 B2 (CALIFORNIA INSTITUTE OF TECHNOLOGY) 30 September 2014 Abstract; Figures 1, 20; Column 5 lines 48-63, column 6 line 2, columns 12-13; Claims 24, 25	1-18
A	US 2012/0301069 A1 (GOLDRING et al.) 29 November 2012	
A	WO 2012/173620 A1 (HEWLETT-PACKARD DEVELOPMENT COMPANY, L.P.) 20 December 2012	
A	WO 2009/075684 A1 (HEWLETT-PACKARD DEVELOPMENT COMPANY, L.P.) 18 June 2009	
A	US 7751655 B2 (FATTAL et al.) 06 July 2010	

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
the subject matter listed in Rule 39 on which, under Article 17(2)(a)(i), an international search is not required to be carried out, including
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See Supplemental Box for Details

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-18

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

Supplemental Box**Continuation of: Box III**

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

- Claims 1 to 18 are directed to a tunable optical device. No features are specific to this group of claims.
- Claims 19 to 20 are directed to a fabrication method for an optical ring cavity. The feature of heating the ring cavity to cause reflow of the structure, in a manner which doesn't cause damage to the electrodes is specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. The only feature common to all of the claimed inventions and which provides a technical relationship among them is an optical ring cavity with capacitive tuning via electrodes. However this feature does not make a contribution over the prior art because it is disclosed in:

US 8849075 B2 (CALIFORNIA INSTITUTE OF TECHNOLOGY) 30 September 2014

Therefore in the light of this document this common feature cannot be a special technical feature. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied a posteriori.

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2016/050644	
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 8849075 B2	30 September 2014	US 2013121633 A1	16 May 2013
		US 8849075 B2	30 Sep 2014
		AU 2011316955 A1	30 May 2013
		AU 2012205511 A1	18 Jul 2013
		AU 2012217606 A1	09 May 2013
		AU 2012220669 A1	02 May 2013
		AU 2012278963 A1	23 Jan 2014
		AU 2013214801 A1	25 Sep 2014
		AU 2013277083 A1	22 Jan 2015
		AU 2014232707 A1	05 Nov 2015
		AU 2016203811 A1	30 Jun 2016
		AU 2016204018 A1	07 Jul 2016
		CN 103635920 A	12 Mar 2014
		CN 103765453 A	30 Apr 2014
		CN 105144216 A	09 Dec 2015
		EP 2678812 A1	01 Jan 2014
		EP 2810242 A1	10 Dec 2014
		EP 2973276 A1	20 Jan 2016
		HK 1213076 A1	24 Jun 2016
		JP 2016524198 A	12 Aug 2016
		SG 193481 A1	30 Oct 2013
		SG 193510 A1	30 Oct 2013
		SG 11201404555W A	28 Aug 2014
		US 2012215648 A1	23 Aug 2012
		US 8571937 B2	29 Oct 2013
		US 2013246261 A1	19 Sep 2013
		US 9355393 B2	31 May 2016
		US 2012123924 A1	17 May 2012
		US 2012124496 A1	17 May 2012
		US 2012209677 A1	16 Aug 2012
		US 2012209749 A1	16 Aug 2012
		US 2012215701 A1	23 Aug 2012
		US 2012233073 A1	13 Sep 2012
		US 2012239556 A1	20 Sep 2012
		US 2013013499 A1	10 Jan 2013
		US 2013024364 A1	24 Jan 2013
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
Form PCT/ISA/210 (Family Annex)(July 2009)			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2016/050644	
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 2013024371 A1	24 Jan 2013
		US 2013054454 A1	28 Feb 2013
		US 2013151417 A1	13 Jun 2013
		US 2013159081 A1	20 Jun 2013
		US 2013159154 A1	20 Jun 2013
		US 2013166332 A1	27 Jun 2013
		US 2013204886 A1	08 Aug 2013
		US 2013204894 A1	08 Aug 2013
		US 2013218657 A1	22 Aug 2013
		US 2013246215 A1	19 Sep 2013
		US 2013246342 A1	19 Sep 2013
		US 2013290203 A1	31 Oct 2013
		US 2013290234 A1	31 Oct 2013
		US 2014019352 A1	16 Jan 2014
		US 2014052617 A1	20 Feb 2014
		US 2014197234 A1	17 Jul 2014
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		US 2014249999 A1	04 Sep 2014
		US 2014337175 A1	13 Nov 2014
		US 2015019944 A1	15 Jan 2015
		US 2015026049 A1	22 Jan 2015
		US 2015039462 A1	05 Feb 2015
		US 2015046241 A1	12 Feb 2015
		US 2015058162 A1	26 Feb 2015
		US 2015154588 A1	04 Jun 2015
		US 2015220914 A1	06 Aug 2015
		US 2015248664 A1	03 Sep 2015
		US 2016063486 A1	03 Mar 2016
		US 2016232513 A1	11 Aug 2016
		WO 2012054785 A1	26 Apr 2012
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		WO 2012097108 A1	19 Jul 2012
		WO 2012112822 A2	23 Aug 2012
		WO 2012116125 A1	30 Aug 2012
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2016/050644	
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
		WO 2013006725 A2	10 Jan 2013
		WO 2013009660 A1	17 Jan 2013
		WO 2013012876 A1	24 Jan 2013
		WO 2013044175 A1	28 Mar 2013
		WO 2013049329 A1	04 Apr 2013
		WO 2013075071 A1	23 May 2013
		WO 2013090611 A2	20 Jun 2013
		WO 2013116806 A1	08 Aug 2013
		WO 2013192443 A1	27 Dec 2013
		WO 2014011691 A1	16 Jan 2014
		WO 2014145708 A1	18 Sep 2014
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2016/050644	
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 2012/0301069 A1	29 November 2012	US 2012301069 A1	29 Nov 2012
		US 8447145 B2	21 May 2013
		CN 102016977 A	13 Apr 2011
		CN 102016978 A	13 Apr 2011
		EP 2266111 A1	29 Dec 2010
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		JP 2011513791 A	28 Apr 2011
		JP 2011514559 A	06 May 2011
		KR 20100128304 A	07 Dec 2010
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		US 8195011 B2	05 Jun 2012
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		US 2010266233 A1	21 Oct 2010
		US 8385698 B2	26 Feb 2013
US 7751655 B2	06 July 2010	US 2009028487 A1	29 Jan 2009
		US 7751655 B2	06 Jul 2010
		US 2010232738 A1	16 Sep 2010
		US 8059922 B2	15 Nov 2011
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			