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(54) Title: MAGNETOMETER

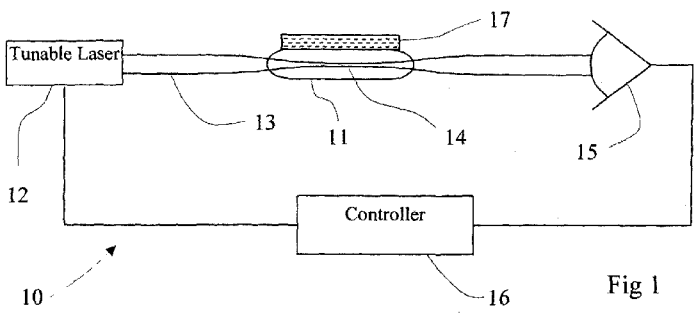


Fig 1

(57) Abstract: A magnetometer comprising a tunable laser producing optical radiation at a laser frequency locked to an optical mode frequency of a microcavity and coupled into the microcavity. The microcavity is coated with a magnetostrictive material with mechanical modes that change when the magnetostrictive material is influenced by a micro-magnetic field. An optical detector detects the optical radiation influenced by the microcavity and generates a signal which is a direct measure of the micro-magnetic field.

TITLE

Magnetometer

FIELD OF THE INVENTION

The present invention relates to the field of micro-magnetic field measurement. More particularly, the invention relates to a device and method useful in diagnostic neuroimaging and similar applications.

BACKGROUND TO THE INVENTION

Detailed understanding of human brain activity requires the ability to perform non-invasive imaging of its activity, preferably with high spatial and temporal resolution. Magneto-encephalography (MEG) is currently the most commonly used method and relies on having highly sensitive magnetometers which can detect relatively low magnetic field (10 femto Tesla to 1 pico Tesla) produced by the neurons in the human brain.

One of the major issues in the treatment of brain trauma is performing non-invasive imaging with high resolution. Better resolution allows for a more precise definition of the region of damage and therefore leads to less invasive surgery.

Superconducting QUantum Interference Devices (SQUIDs) are the most commonly used technology in MEG and can measure magnetic fields of 1 fT/Hz. However, they require liquid helium cooling, in order to achieve sufficient sensitivity, which makes them relatively expensive and bulky. Preferably, one needs a large number of sensors with a high temporal resolution as close as possible to the source to maximize the spatial resolution and increase the signal to noise ratio. SQUID-arrays used for tomography are limited to a maximum of, typically, a hundred sensors. The size and the distance to the source, together with the low bandwidth, limit the spatial resolution achievable for tomography using an array of multiple SQUIDs to typically ten millimetres.

In recent years a new magnetic neural imaging method has been developed to overcome this issue called functional magnetic resonance imaging (fMRI). Functional MRI can directly monitor magnetic brain activity and the resolution of the tomography is determined by an external magnetic field gradient combined with a single magnetic field sensor. This increases the spatial resolution compared to MEG to typically several millimetres, but the large background magnetic field required increases the complexity of the system and therefore the costs. Magnetic field sensors also have to work in the presence of relatively large magnetic fields, which greatly increase the technical demands for the sensor.

Microtesla MRI is a recently developed technique that uses a relatively small background magnetic field, which greatly reduces complexity and cost. This technique needs a magnetic field sensor that is very sensitive and can operate in the presence of (switched) external fields. SQUIDs are used for this purpose, but are technically challenging to implement, increase the cost and reduced the mobility of such a system.

As an alternative to SQUIDS it is possible to use atomic magnetometers based on nonlinear magneto-optical rotation in alkali-metal vapours. These sensors show similar sensitivities to SQUIDs, but have other technical challenges.

OBJECTS OF THE INVENTION

It is an object of the present invention to overcome or at least alleviate one or more of the above limitations with known magneto-imaging devices and techniques.

It is a further object to provide a magneto-imaging device that is more compact and economic than known devices.

SUMMARY OF THE INVENTION

In one form, although it need not be the only or indeed the broadest form, the invention resides in a microcavity for a magnetometer wherein the microcavity is coated with a magnetostrictive material. The magnetometer includes a source of optical radiation and a detector, whereby a magnetic field that causes a change in the magnetostrictive material causes a detectable change in the optical radiation.

In a further form, although again not necessarily the broadest form, the invention resides in a magnetometer comprising:
a microcavity having optical modes and mechanical modes;
a tunable laser producing optical radiation at a laser frequency locked to an optical mode frequency of the microcavity and coupled into the microcavity;
a magnetostrictive material coated on the microcavity such that the mechanical modes change when the magnetostrictive material is influenced by a magnetic field; and
an optical detector that detects the optical radiation influenced by the microcavity.

Preferably the microcavity is a microtoroid. The optical mode frequency of the microcavity is related to the length of the microcavity. The mechanical modes are related to vibrations of the microcavity.

Suitably the changes in mechanical modes are detected as a change in signal amplitude or frequency at the detector.

Preferably the optical radiation is coupled to the microcavity by an optical fibre. The coupling is suitably evanescent coupling.

In a still further form, the invention resides in a method of detecting micro-magnetic fields including the steps of:
positioning a microcavity coated with a magnetostrictive material in a micomagnetic field;

coupling optical radiation into the microcavity, the optical radiation having a frequency locked to an optical mode frequency of the microcavity;
detecting optical radiation influenced by mechanical modes of the microcavity and generating a detection signal;
measuring changes in the detection signal as a measure of the micro-magnetic field.

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

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:

FIG 1 is a schematic block diagram of a magnetometer;

FIG 2 demonstrates microtoroid cavity modes;

FIG 3 demonstrates the effect of tuning the laser of the magnetometer;

FIG 4 shows the principle of the magnetostrictive effect;

FIG 5 shows an example of the magnetostrictive effect in a magnetometer;

FIG 6 shows an experimental set up for demonstrating the invention; and

FIG 7 shows results obtained from the set up of FIG 6.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention reside primarily in a magnetometer constructed from a microtoroid coated with a magnetostrictive material and a source of optical radiation. Accordingly, the elements of the device and the method steps of operation 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 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 a shown a schematic of a magnetometer particularly suited for neuroimaging. The device of FIG 1 is not limited to the neuroimaging application but it is convenient to describe the device in terms of this application because it is considered to be a major application. The magnetometer may also be useful in magnetocardiography, magnetoencephalography, geophysics, defence and mining where detection of micro-magnetic fields is required.

The magnetometer 10 comprises a microtoroid 11 coupled to a tunable laser 12 by an optical fibre 13. Any tunable laser may be chosen that generates an output at an appropriate frequency for the cavity modes of the microtoroid, as explained below. However, it has been found that a tunable diode laser is appropriate for the preferred embodiment.

Optical output from the laser diode 12 is evanescently coupled into the microtoroid by an optical fibre 13 and is coupled out of the microtoroid 11 by the same optical fibre 13. The optical fibre 13 has a tapered portion 14 that abuts the microtoroid 11. The tapering of the optical fibre degrades the optical guiding so that some of the light 'leaks' from the fibre and is coupled into the microtoroid. The effect is maximised when the frequency of light in the fibre matches an optical cavity mode of the microtoroid. This is shown schematically in FIG 2 which also depicts evanescent coupling 18. A trace of a scan of the frequency of light emitted from the laser 12 shows high transmitted power when the optical frequency does not match the cavity frequency. When the optical frequency and

cavity frequency match, more light is coupled into the micotoroid and this is evident in the trace of the transmitted power, as seen in FIG 2.

The optical fibre used in the preferred embodiment is typical of those used in telecommunications. The specific fibres are unimportant providing they effectively couple light to and from the microtoroid. Any other coupling device such as side polished fibre or a free space prism coupler would also be suitable. Optical fibres are preferred due to low noise and low crosstalk. Light exiting the optical fibre 13 is detected by a photodiode 15, although any suitable detector can be used and will be selected to suit the specific wavelength of the chosen laser and microtoroid cavity frequency. In the preferred embodiment the detector 15 is an InGaAs photodiode.

For the purpose of describing the preferred embodiment, the tunable diode laser 12 operates at a wavelength of 1544nm and is sourced from New Focus of San Jose, California, United States of America. In principle, other lasers can be used with preferably better noise characteristics. However, it is important that the laser can be tuned over a sufficiently large range to cover all the optical modes of the microcavity.

The magnetometer 10 comprises a microcavity 11 in the form of a toroid, shown more clearly in FIG 2. Other possible cavities include but are not limited to a microdisk cavity, a fabry-perot cavity, a microsphere cavity or some other cavity optomechanical system (COMS). The microcavity 11 is fabricated on a silicon chip using photolithography and dry etching. For the purposes of constructing a preferred embodiment the inventors have relied upon known fabrication processes common in production of computer chips and semiconductor devices. Persons skilled in the art will appreciate that the invention is not limited to any particular fabrication process. Any process that produces a dielectric micro-scale cavity will be suitable.

Characteristically these optical microcavities have an extremely high Q-factor of typically 10^8 and a relatively small size of typically 100 μm.

The signal from the detector 15 is fed back to the laser controller 16. A phase lock loop is suitably employed to lock the laser output to the optical cavity

mode. One approach for controlling the laser frequency is shown in FIG 3. An error signal is generated that tracks the change in detected power and the controller provides a tuning signal that shifts the laser output in response to the tuning signal. The tuning signal can be monitored so that any change in the cavity frequency is immediately evident.

When the laser is locked to an optical cavity mode and the frequency spectrum of the lock signal is measured, a number of fine structure peaks are observed. The fine structure in the frequency spectrum comes from mechanical modes of the microcavity. These mechanical modes arise from thermal vibration. When the microcavity vibrates with certain frequency and amplitude, the cavity length changes at that frequency.

The microtoroid of the preferred embodiment is coated with a magnetostrictive material 17. Magnetostriction is a property of ferromagnetic materials that causes them to change their shape or dimensions when exposed to a magnetic field. Qualitatively, this can be explained by the fact that ferromagnetic materials have a structure that is divided into domains, each of which is a region of uniform magnetic polarization. When a magnetic field is applied, the boundaries between the domains shift and the domains rotate. Both of these effects cause a change in the material's dimensions. Magnetostriction can be quantified by the magnetostrictive coefficient εM, which is the fractional change in length as the magnetization of the material increases from zero to the saturation value. For most ferromagnetic materials, such as nickel, this coefficient is rather small (10^{-6} T^{-1}), but several alloys have been developed to maximize this effect such as Galfenol and Terfenol-D [these materials are described in C. Rodriquez et al, Sensors and Actuators A, 149 (2009)], where the latter has a magnetostrictive coefficient $\varepsilon M = 4 \cdot 10^{-2}$ T^{-1}. To be able to measure this effect in these alloys caused by neural magnetic fields of 10^{-12} T means that one needs a sensor (having diameter D) that can detect a strain of $\varepsilon M \cdot 10^{-12}$, or deformations of $D \cdot \varepsilon M \cdot 10^{-12}$ m. Terfenol-D is an alloy of Terbium, Iron and Dysprosium of the formula $Tb_xDy_{1-x}Fe_2$ with $x \sim 0.3$. Galfenol is a general term for alloys of iron and gallium.

The microtoroid detects this deformation by a mechanism similar to that depicted in FIG 4. The change in dimension of the magnetostrictive material 17 strains the microtoroid 11 so that the mechanical modes change slightly. The change in mechanical modes changes the cavity frequency spectrum so that the amplitude of transmitted light changes, thus generating a measurable signal at the detector. The magnitude of the magnetostrictive effect is directly related to the applied magnetic field strength, and the magnitude of the magnetostrictive effect can be determined by measuring changes in the signal at the detector. The changes may be amplitude or frequency changes. Thus, the micro-magnetic field generated by the human brain is detected directly by analysing the signal at the detector 15.

The magnetostrictive material may be applied to the microcavity using various techniques such as gluing or direct deposition using masks. Other techniques will be known to persons skilled in the field.

The efficacy of the invention is shown by the series of traces in FIG 5. For this experiment two microtoroids are compared, one with and one without Terfenol-D, where both toroids are exposed to a modulating magnetic field. To enhance the effect that the magnetostriction has on the change of the cavity length of the cavity, the frequency of the modulation of the magnetic field is chosen to be at one of the mechanical resonances of the microtoroid at 9730 KHz. The top figure shows the response of the microtoroid without the Terfenol-D and shows two traces; one with zero amplitude modulation and one with amplitude of 0.08 μT. As expected, there was no response. The middle figure shows the response of the microtoroid with a Terfenol-D coating. This figure shows a clear difference in response (~10dB) to the modulated magnetic field compared to zero amplitude. Finally, the last figure shows the response of the microtoroid with the Terfenold-D at a broader mechanical mode at a frequency of 10360 kHz, with a smaller response (~5dB) when exposed to the same modulated magnetic field, which is expected when this resonance is mechanically driven. Therefore, this proves that the effect is purely mechanical and it must follow from the mechanical drive of the magnetostrictive material that is present on the microtoroid.

Another proof-of-principle embodiment of the invention is shown in FIG 6. A piece of Terfenol-D (Etrema Products Inc.) with a size of roughly 50 μm x 15 μm x 10 μm was affixed to the top surface of a TWGM (toroidal whispering gallery mode) resonator by using micromanipulators and two-component epoxy. The TWGM resonator had major and minor diameters of 60 μm and 6 μm, respectively, and a 10 μm undercut. The TWGM resonator was placed between two 20 mm diameter coils that generated an HF magnetic field previously calibrated with a commercial Hall sensor. Light of 980 nm from a widely tunable, external cavity diode laser was passed through a fiber polarization controller and evanescently coupled to the resonator via a tapered optical fiber. The laser was thermally locked to the full width at half maximum of an optical resonance. Mechanical vibrations of the TWGM resonator shift its optical resonances and thus modulate the transmitted light that is detected with an InGaAs photodiode.

The transduction spectrum shown in FIG 7(a) was obtained by analysing the transmitted light with a spectrum analyser. It shows multiple characteristic peaks corresponding to thermally excited mechanical modes. With a finite element solver the three vibrational modes around 10 MHz were identified as the lowest order flexural mode (center) and the two lowest order crown modes. Application of a 250 μT magnetic field at $\omega_{ref} = 2\pi$ x 10:38 MHz resulted in a signal at that frequency above the Brownian noise, confirming the ability of the sensor to detect magnetic fields.

The magnetic field sensitivity was determined by:

$$B_x^{min}(\omega_{ref})/\Delta\omega^{1/2} = |B_x|/\sqrt{SNR(\omega_{ref})\Delta\omega_{RBW}},$$

where SNR is the signal-to-noise ratio, B_x is the applied magnetic field in direction x, and $\Delta\omega_{RBW}$ is the resolution bandwidth of the spectrum analyser.

To determine the sensitivity over a wide frequency range, a network analyser was used to scan the frequency of the magnetic field from 7 to 13 MHz and simultaneously detect the systems response $N(\omega)$. As expected, FIG 7(b) shows a Lorentzian line-shaped peak distribution similar to the Brownian noise

spectrum of FIG 7(a), with an additional peak present around 11.5 MHz, due to the enhanced noise rejection of the phase sensitive network analyser. In both cases the measured data agree quite well with a model with five mechanical resonances. The inset in FIG 7(b) shows the system response centred around 10.385MHz.

A single magnetometer has been described. It will be understood that an array of several hundred magnetometers is required for neuroimaging. The magnetometer described above is compact, relatively low cost, and the use of optical fibres eliminates crosstalk. Thus, for the first time, there is a magnetometer that can be used to construct large, close packed arrays of devices capable of delivering better spatial resolution than previously achievable.

The above description of various embodiments of the present invention is provided for purposes of description to one of ordinary skill in the related art. It is not intended to be exhaustive or to limit the invention to a single disclosed embodiment. As mentioned above, numerous alternatives and variations to the present invention will be apparent to those skilled in the art of the above teaching. Accordingly, while some alternative embodiments have been discussed specifically, other embodiments will be apparent or relatively easily developed by those of ordinary skill in the art. Accordingly, this invention is intended to embrace all alternatives, modifications and variations of the present invention that have been discussed herein, and other embodiments that fall within the spirit and scope of the above described invention.

CLAIMS

1. A microcavity for a magnetometer wherein the microcavity is coated with a magnetostrictive material.

2. The microcavity of claim 1 wherein the magnetostrictive material is Terfenol-D.

3. The microcavity of claim 1 wherein the microcavity is a microtoroid.

4. A magnetometer comprising:
a microcavity having optical modes and mechanical modes;
a tunable laser producing optical radiation at a laser frequency locked to an optical mode frequency of the microcavity and coupled into the microcavity;
a magnetostrictive material coated on the microcavity such that the mechanical modes change when the magnetostrictive material is influenced by a magnetic field; and
an optical detector that detects the optical radiation influenced by the microcavity.

5. The magnetometer of claim 4 wherein the microcavity is a microtoroid.

6. The magnetometer of claim 4 wherein the microcavity is selected from one of: a microdisk cavity; a Fabry-Perot cavity; or a microsphere cavity.

7. The magnetometer of claim 4 wherein the microcavity has a Q-factor of around 10^8.

8. The magnetometer of claim 4 wherein the tunable laser is a laser diode.

9. The magnetometer of claim 4 wherein the optical radiation is coupled into the microcavity by one of: an optical fibre; a side polished fibre; or a free space prism.

10. The magnetometer of claim 4 further comprising an optical fibre wherein the optical radiation is coupled into the microcavity by evanescent coupling.

11. The magnetometer of claim 4 further comprising a phase lock loop between the optical detector and the tunable laser to lock the laser frequency to an optical mode.

12. The magnetometer of claim 4 wherein the magnetostrictive material is an alloy including iron and terbium.

13. The magnetometer of claim 12 wherein the magnetostrictive material is Terfenol-D.

14. The magnetometer of claim 4 wherein the magnetostrictive material is an alloy including iron and gallium.

15. The magnetometer of claim 4 wherein the optical detector is an InGaAs photodiode.

16. A method of detecting micro-magnetic fields including the steps of:
positioning a microcavity coated with a magnetostrictive material in a micro-magnetic field;
coupling optical radiation into the microcavity, the optical radiation having a frequency locked to an optical mode frequency of the microcavity;
detecting optical radiation influenced by mechanical modes of the microcavity and generating a detection signal; and
measuring changes in the detection signal as a measure of the micro-magnetic field.

17. The method of claim 16 further including the step of directing the optical radiation to an optical fibre that abuts the microcavity and coupling the optical radiation to the microcavity by evanescent coupling.

18. The method of claim 16 further including the step coupling the optical radiation from the microcavity to an optical fibre by evanescent coupling

19. The method of claim 18 wherein the step of detecting optical radiation includes directing the optical radiation from the optical fibre to a detector.

20. The method of claim 16 wherein the frequency of the optical radiation is locked to an optical mode frequency of the microcavity with a phase lock loop.

21. The method of claim 16 wherein the micro-magnetic field is selected from one of: a neural field; or a geophysical field.

5

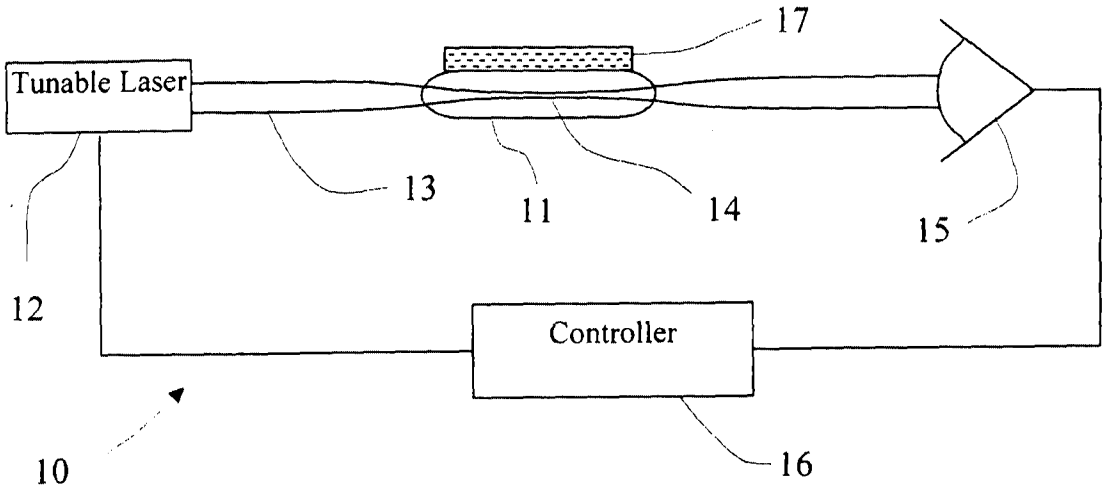

Tunable Laser
17
13
11
14
15
12
Controller
10
16

Fig 1

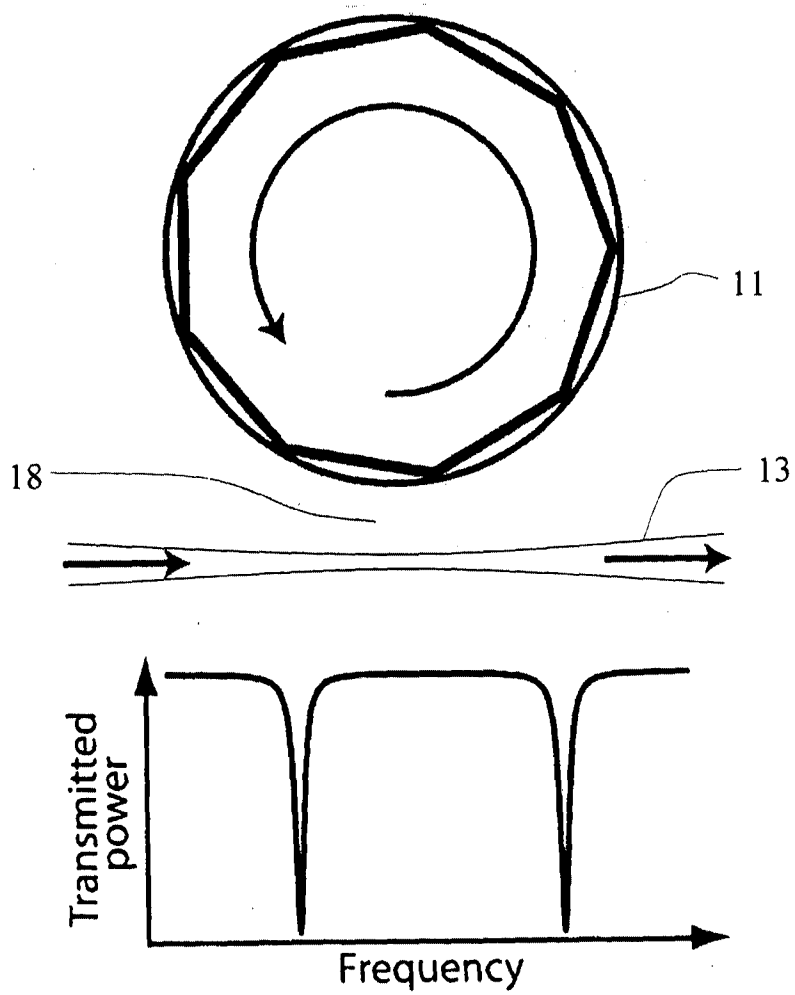

11
18
13
Transmitted power
Frequency

Fig 2

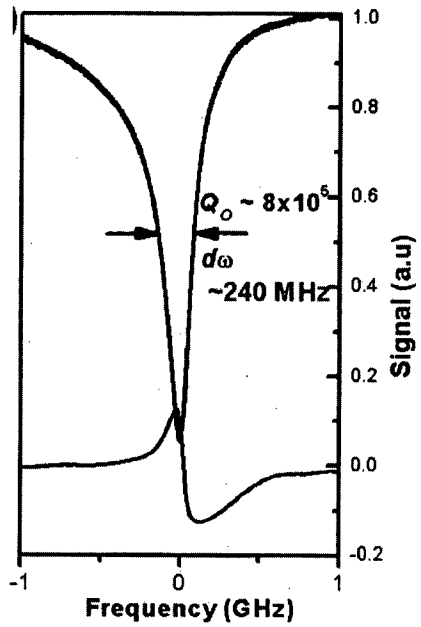

1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Signal (a.u)
Q_o ~ 8x10^6
dω
~240 MHz
-1
0
1
Frequency (GHz)

Fig 3

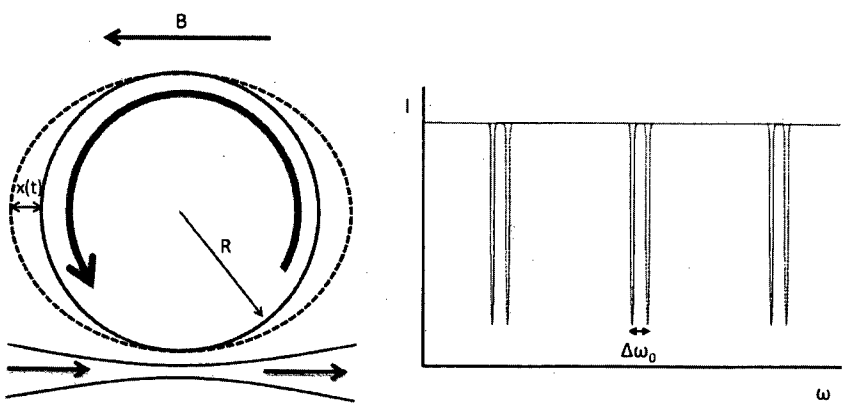

B
x(t)
R
I
Δω$_0$
ω

Fig 4

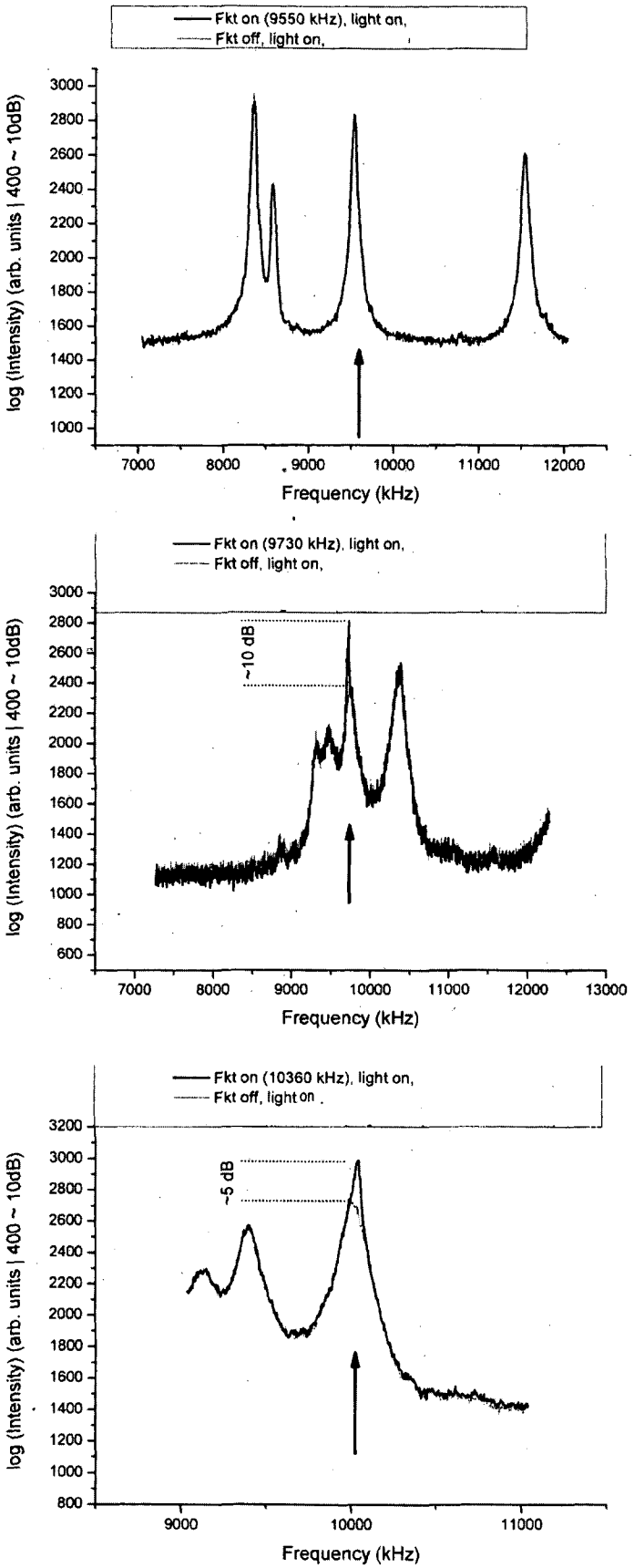

Fkt on (9550 kHz), light on,
Fkt off, light on,
log (Intensity) (arb. units | 400 ~ 10dB)
Frequency (kHz)
Fkt on (9730 kHz), light on,
Fkt off, light on,
~10 dB
log (Intensity) (arb. units | 400 ~ 10dB)
Frequency (kHz)
Fkt on (10360 kHz), light on,
Fkt off, light on,
~5 dB
log (Intensity) (arb. units | 400 ~ 10dB)
Frequency (kHz)

Fig 5

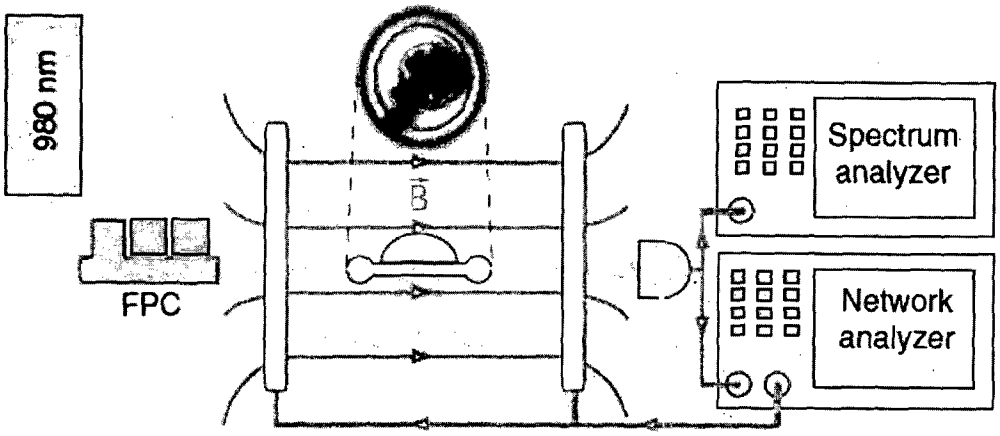

980 nm
FPC
B
Spectrum analyzer
Network analyzer

Fig 6

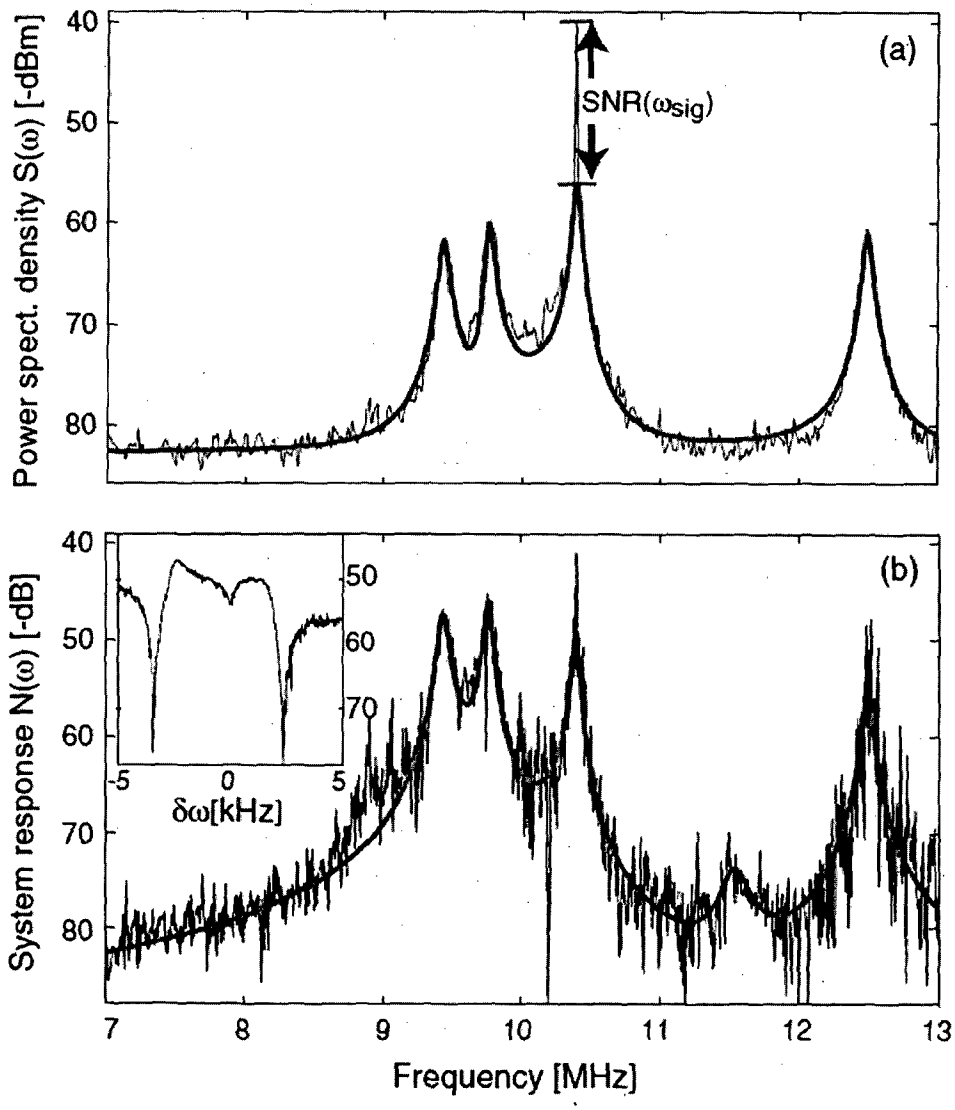

Power spect. density S(ω) [-dBm]
40
50
60
70
80
(a)
SNR(ωsig)
System response N(ω) [-dB]
40
50
60
70
80
(b)
50
60
70
-5
0
5
δω[kHz]
7
8
9
10
11
12
13
Frequency [MHz]

Fig 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2012/000395

A. CLASSIFICATION OF SUBJECT MATTER

G01R 33/05 (OCT 2005) G01D 5/353 (OCT 2005) G01B 9/00 (OCT 2005) G01R 33/18 (OCT 2005)

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)

WPI, EPODOC, INSPEC, Google Patents: magnetometer, measure magnetic field, cavity, resonator, magnetostrictive, coat, laser and similar key words.

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	

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

* Special categories of cited documents:

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 July 2012	03 July 2012

Name and mailing address of the ISA/AU

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INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	**PCT/AU2012/000395**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/0148770 A1 (CROWE) 17 June 2010 Abstract, fig. 1, 2B, 4, para.[0011]-[0015], [0020]	1-10, 12-19, 21
A	WO 2002/090881 A1 (PRECISION PHOTONICS CORPORATION) 14 November 2002 Page 1 line 10 – page 2 line 6	4-5, 8-11, 16-20

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2012/000395**

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 2010/0148770 A1	17 Jun 2010	US 2010148770 A1	17 Jun 2010
		US 8125644 B2	28 Feb 2012
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		US 6621580 B2	16 Sep 2003
		US 2003035120 A1	20 Feb 2003
		WO 02090881 A1	14 Nov 2002
		WO 03016814 A1	27 Feb 2003

End of Annex

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