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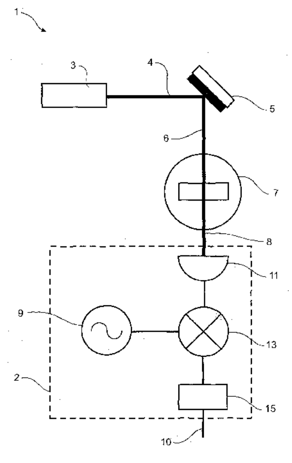

FIGURE 1

(57) Abstract: A method and apparatus for detecting ultrasound vibrations of a subject (5) is disclosed. The method comprises passing a modulated beam (6) from a vibrating subject through a resonant medium (7). The beam (4) has a carrier frequency component and two major sideband frequency components. The resonant medium (7) imparts a phase shift on the carrier frequency component and passes the two major sideband frequency components to output an amplitude modulated signal. The ultrasound vibrations of the subject (5) can be detected from the amplitude modulated signal.

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METHOD AND APPARATUS FOR DETECTION OF ULTRASOUND

Field of the invention

The present invention relates to a method and apparatus for detecting ultrasound vibrations using a resonant medium.

Background of the invention

Ultrasonics is an established field with important applications in both medical imaging as well as engineering.

The field of ultrasonics relates to the generation and detection of ultrasonic vibrations. Ultrasonic vibrations aire generated when acoustic waves are propagated through a medium. In general, these vibrations have frequencies of 50 kHz—20 MHz. One of the main properties of waves in this frequency domain is their ability to penetrate into surfaces. The main source of attenuation is due to absorption and scattering from discontinuities in the medium of propagation. However, for subjects such as biological tissue ultrasonic waves only suffer moderate attenuation. For example, depending on the wave frequency and the medium of propagation, ultrasonic waves can propagate up to several meters in metal. Like other wave motions, ultrasonic waves can be reflected and refracted at boundaries in the medium. High resolution can also be achieved due to the high frequencies, and therefore short wavelengths, used. The wavelength of the ultrasound can be determined using the phase speed.

The high penetration depth and the reflection of ultrasonic waves at boundaries make these waves a useful diagnostic tool for non-invasive, non-destructive testing or imaging. For example, diagnostic sonography techniques are widely used in medical diagnostic tools in areas such as in obstetrics, gynaecology, and cardiology (to name a few) as these techniques are fast, have high resolution and are relatively painless. This allows, for example in biological imaging applications, detection of oxygenated and deoxygenated blood thus allowing mapping of its associated vessels in a sample. The ability to resolve fine structures have also allowed imaging of structures such as the carotid artery. In the industry, ultrasound is used to measure thicknesses of coatings on various substrates such as adhesive bonding, and strength of joints such as rock bolts. Ultrasound has been utilised in non-destructive imaging techniques such as acoustic microscopy which allows deep features to be resolved, such as embedded microchips. Measurements using ultrasound are performed by first generating ultrasonic waves at the subject or sample of interest. This can be done, for example, by placing a piezo-electric transducer with coupling media in contact with the subject or sample to be probed. The waves then propagate within the sample and are reflected at density boundaries of the sample. These reflected waves are then detected using another, possibly separate, transducer.

Most existing methods require both the emitting and receiving transducers to have physical contact with the subject being probed to detect the ultrasound vibrations. In recent years, interest has been directed towards the remote detection of ultrasonic vibrations. Much of the work put into this field utilises optical beams reflecting off ultrasonically vibrating surfaces. The vibration is then detected using interferometers to detect the modulated light — Park et al., Measurement Science and Technology 16 (2005) 1261-1266. However, there exists a limitation to the sensitivity that can be achieved by these optical methods due to the low light-gathering power, or etendue, of the interferometers. To obtain high signal-to-noise ratios, the interferometer needs to be able to collect as much light as possible, hence a high etendue is beneficial. In interferometric systems, the mode of the signal light must match the reference beam in order-for the two to interfere. This results in a very low effective etendue.

Recent work by Li et al., Vol 16, No 19/Optics Express 14862, has demonstrated the detection of ultrasound using spectral hole burning of a rare-earth ion doped crystal to detect the frequency sidebands relating to ultrasonic modulation of light from a sample. In Li, a spectral hole is burnt in the rare-earth material to allow one sideband of the reflected wave from the sample to propagate through the rare-earth crystal while blocking the carrier signal and other sidebands. When the ultrasound signal is weak, the intensity of the carrier signal will be much higher than the sidebands. Therefore, in order to detect weak ultrasound using the method of Li, high attenuation at the carrier frequency is needed at the same time as good transmission of the transmitted sideband. This method requires high optical thickness in the attenuating regions yet being transparent at the sideband frequency, which can be difficult to achieve. This very large contrast in the absorption in the rare-earth ion doped crystal is hard to realise in practice..

Korneev et al., Optics Letters, Vol 34, No 13 describes a system for detection of ultrasound. The system requires the preparation of a complex dynamic hologram in a material, and the dynamic hologram is used as the basis for an adaptive interferometer. In the Korneev system, the information-carrying sidebands will be heavily attenuated, which will result in limited sensitivity. The Korneev system is sensitive to ultrasound down to about 1 MHz.

US 6,535,328 describes the use of Brillouin scattering in fibers. Brillouin scattering is an interaction between light and acoustic vibrations. Brillouin scattering can, amongst other things provide reasonably narrow gain features (13MHz) to optical fields. The document describes using those gain features for signal processing operations in telecommunications systems. While the system of that document uses acoustic vibrations to get an interaction between two different light fields, the acoustic vibrations used are of very high frequency (in the order of 10GHz).

That document suggests converting from phase modulation to amplitude modulation by selective amplification of one sideband, which would result in a narrow bandwidth. Additionally, while the gain features are narrow for some applications, they are significantly wider than those that would be required for efficient detection of ultrasound. Additionally, that system relies on light being in a single mode optical fibre, so the etendue of that system would be no better than that of an interferometer.

It is an object of at least preferred embodiments of the present invention to address at least one of the issues outlined above, or to provide the public with a useful choice.

In this specification where reference has been made to patent specifications, other external documents, or other sources of information, this is generally for the purpose of providing a context for discussing the features of the invention. Unless specifically stated otherwise, reference to such external documents or such sources of information is not to be construed as an admission that such documents or such sources of information, in any jurisdiction, are prior art or form part of the common general knowledge in the art.

It is intended that reference to a range of numbers disclosed herein (for example, 1 to 10) also incorporates reference to all rational numbers within that range (for example, 1, 1.1, 2, 3, 3.9, 4, 5, 6, 6.5, 7, 8, 9 and 10) and also any range of rational numbers within that range (for example, 2 to 8, 1.5 to 5.5 and 3.1 to 4.7) and, therefore, all sub-ranges of all ranges expressly disclosed herein are hereby expressly disclosed. These are only examples of what is specifically intended and all possible combinations of numerical values between the lowest value and the highest value enumerated are to be considered to be expressly stated in this application in a similar manner.

Summary of the invention

A first aspect of the present invention broadly consists in a method of detecting ultrasound vibrations of a subject, the method comprising:

passing a modulated beam from a vibrating subject through a resonant medium wherein the modulated beam has a carrier frequency component and two major sideband frequency components, wherein the resonant medium imparts a phase shift on the carrier frequency component and passes the two major sideband frequency components to output an amplitude modulated signal; and

detecting the ultrasound vibrations of the subject from the amplitude modulated signal.

The term "comprising" as used in this specification means "consisting at least in part of; that is to say when interpreting statements in this specification which include "comprising", the features prefaced by this term in each statement all need to be present but other features can also be present. Related terms such as "comprise" and "comprised" are to be interpreted in a similar manner.

As used herein, a "resonant medium" is a medium in which attenuation and phase shift of light show abrupt changes for small frequency differences due to resonances in constituent parts of the medium. Examples of resonant media include atoms, molecules, dopants and solid state defects.

As used herein, "subject" includes any suitable subject for ultrasound analysis. The subject could be biological (such as a human or animal subject), could be an engineering subject (such as a structure), or could be any of the other examples outlined in the "Background of the invention" section, for example.

The beam that passes to the resonant medium from the vibrating subject may be divergent. References herein to "beam", at least in relation to the beam that passes to the resonant medium from the vibrating subject, should be construed to cover such situations of high divergence, and not only light travelling substantially in the same direction with a very small spread of angles. While the other beams referred to herein will preferably have a small spread of angles, they could also potentially be diverging.

In an embodiment, the resonant medium passes the two major sideband frequency components with zero or minimal attenuation. Alternatively, the other sideband frequency components may be absorbed by the resonant medium.

In an embodiment, the method of detecting ultrasound vibrations comprises the step of transmitting a beam to the vibrating subject, wherein at least part of the transmitted beam interacts with the vibrating subject. The beam may be reflected off the vibrating subject. Alternatively, the beam may pass through the vibrating subject. In an embodiment, the transmitted beam has narrow spectral features. The transmitted beam may have a single stable carrier frequency. The transmitted beam may have a wavelength substantially the same as, or close to, a resonance in the resonant medium. The transmitted beam may have a wavelength close to a narrow peak in the resonant medium's absorption spectrum. In an embodiment, the peak is less than about 2 nm wide. In an embodiment, the wavelength of the transmitted beam is closer to a centre of the peak than forty times the full-width half-maximum width of the peak. In an embodiment, the transmitted beam is a laser beam.

The modulated beam that is passed from the vibrating subject through the resonant medium may be a phase modulated beam.

In an embodiment, the resonant medium imparts a phase shift of substantially 90° on the carrier frequency component of the modulated beam.

In an embodiment, the amplitude modulated signal comprises a carrier signal component with an amplitude that is modulated by a modulation signal having a modulation frequency, wherein the modulation frequency is proportional to the vibrations of the subject. The modulation frequency may be proportional to the difference between the carrier frequency of the modulated beam and one of the two major sideband frequency components. The step of detecting the ultrasound vibrations may involve the step of detecting the modulation signal. The modulation signal may be detected using a homodyne apparatus. Alternatively, the modulation signal may be detected using a heterodyne apparatus. The modulation signal may be detected using a digital signal processor.

In one embodiment, the resonant medium comprises a rare-earth ion doped crystal, and the method comprises- spectrally hole burning a hole in the crystal. In an embodiment, the hole is slightly offset from the carrier frequency component of the modulated beam to impart the phase shift on the carrier frequency component of the modulated beam. In an embodiment, the hole is near the carrier frequency component and has relatively wide trenches either side to allow the major sideband frequency components through without any attenuation or phase shift. Alternatively, the hole may have an edge near the carrier frequency component of the modulated beam and may have relatively wide trenches either side to allow the major sideband frequency components through without any attenuation or phase shift. Alternatively, the resonant medium comprises a rare-earth ion doped crystal, in which more than one hole has been spectrally burned.

In an embodiment, the ion(s) doped in the crystal is/ are selected from the group comprising Praseodymium (Pr), Neodymium (Nd), Europium (Eu), Erbium (Er), ThuKum (Tm), Ytterbium (Yb). In an embodiment, the ion(s) is/ are Tm^{3+}. In an embodiment, the crystal is selected from the group comprising lanthanum fluoride (LaF_3), Yttrium orthosiliate (Y,SiO_5), Yttrium (III) Vanadate (YVO_4), Yttnum-Aluminium-Garnet (YAG). In an embodiment, the resonant medium comprises Tm^{3+} ions doped in a YAG crystal. The spectral hole(s) may be burnt into the rare-earth crystal before the modulated beam is passed through the crystal. Alternatively, the spectral hole(s) may be burnt into the rare-earth crystal concurrently with the modulated beam being passed through the crystal.

In an embodiment, in the case of a rare-earth doped crystal, the transmitted beam has a wavelength substantially the same as a resonance in the resonant medium. In the case of Tm^{3+} ions doped in a YAG crystal, the transmitted beam may have a wavelength of about 793.38 nm. The frequency is suitably somewhere in the frequency range where the Tm ions absorb. The width of this region is somewhat crystal dependent, and in some embodiments of the present invention is about 30 GHz wide. The method may comprise holding the resonant medium is at a cryogenic temperature, such as about 4K for example. In an embodiment, the temperature is less than about 10 K. In the case of Tm^{3+} ions doped in a YAG crystal, the temperature may be less than about 3 K.

In an embodiment, the method comprises transmitting a laser beam from a laser source to the vibrating subject, wherein at least part of the laser beam interacts with the subject; and performing frequency stabilization on the laser beam. The step of performing frequency stabilisation may comprise using a combination of optical and electronic feedback to the laser. The step of performing frequency stabilisation may comprise using part of the laser beam that has passed through the resonant medium for optical feedback and part of the laser beam that has passed through the resonant medium for electronic feedback. The step of performing frequency stabilisation may comprise the step of delivering a part of the laser beam that has passed through the resonant medium to a detector, to determine the frequency difference between the laser beam and a spectral hole in the resonant medium and from the frequency difference, adjusting the laser beam frequency substantially to the Centre of the spectral hole. The step of performing frequency stabilisation may comprise delivering a part of the laser beam that has passed through the resonant medium back into the laser source to provide optical feedback to the laser.

In an alternative embodiment, the resonant medium comprises a gas or vapour which is adapted to function as a sharp frequency discriminator. The resonant medium may comprise a molecular gas or an atomic vapour. In an embodiment, the gas or vapour comprises an alkali metal vapour. In an embodiment, the gas or vapour is selected from the group comprising lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb), iodine, ammonia, acetylene, Cesium (Cs).

The method may comprise passing a signal from a coupling beam and the modulated beam, into the gas or vapour. The coupling beam and the modulated beam may be detuned away from a doppler broadened transition of the gas or vapour, to make use of offresonant Raman transitions. The method may comprise passing the coupling beam and the modulated beam through a polarising beam splitter and directing the signal that is output from the beam splitter into the gas or vapour. The coupling beam may be obtained from a beam that is transmitted to the subject.

In an embodiment, in the case of atomic vapour or molecular gas, the transmitted beam has a wavelength close to, or substantially the same as a resonance in the resonant medium.

The gas or vapour may be at ambient or room temperature (between about 20°C and about 25°C). When an atomic vapour is used, the vapour may be between room temperature and about 150°C.

A second aspect of the present invention broadly consists in an apparatus for detecting ultrasound vibrations of a subject, wherein the apparatus is adapted to receive a modulated beam from the subject, the modulated beam having two major sideband components and a carrier frequency component, the apparatus comprising:

a resonant medium adapted to pass the major sideband frequency components and to pass the carrier frequency component and impart a phase shift on the carrier frequency component to convert the modulated beam to an amplitude modulated signal;

the apparatus configured to detect the ultrasound vibrations from the amplitude modulated signal.

In an embodiment, the resonant medium passes the two major sideband frequency components of the beam with minimal or zero attenuation.

In an embodiment, the apparatus comprises a transmitter for transmitting a beam to the vibrating subject, wherein at least part of the beam interacts with the vibrating subject. The beam may reflect off or pass through the vibrating subject. The transmitted beam may have narrow spectral features. The transmitted beam may have a single stable carrier frequency. The transmitted beam may have a wavelength substantially the same as, or close to, a resonance in the resonant medium. The transmitted beam may have a wavelength close to a narrow peak in the resonant medium's absorption spectrum. In an embodiment, the peak is less than about 2 nm wide. The wavelength of the beam may be closer to a centre of the peak than forty times the full-width half-maximum width of the peak. In an embodiment, the transmitted beam is a laser beam.

In an embodiment, the resonant medium imparts a phase shift of substantially 90° on the carrier frequency component of the modulated beam.

In an embodiment, the amplitude modulated signal comprises a carrier signal component with an amplitude that is modulated by a modulation signal having a modulation frequency, wherein the modulation frequency is proportional to the vibrations of the subject. In an embodiment, the apparatus comprises a detector for detecting the ultrasound vibrations, wherein the detector is adapted to detect the ultrasound vibrations from the modulation signal. The detector may comprise a homodyne apparatus. Alternatively, the detector may comprise a heterodyne apparatus. The detector may comprise a digital signal processor.

In an embodiment, the apparatus is adapted for remote detection of ultrasound, wherein no part of the apparatus, other than the beam, physically contacts the subject.

In one embodiment, the resonant medium comprises a rare-earth ion doped crystal, in which a hole has been spectrally burned into the crystal. The hole may be slightly offset from the carrier frequency component of the beam to impart the phase shift on the carrier frequency component of the modulated beam. In an embodiment, the hole is near the carrier frequency component and has relatively wide trenches either side to allow the major sideband frequency components through without any attenuation or phase shift. Alternatively, the hole may have an edge near the carrier frequency component of the modulated beam and may have wide trenches either side to allow the major sideband frequency components through without any attenuation or phase shift. The resonant medium may comprise a rare-earth ion doped crystal in which more than one hole has been spectrally hole burned into the crystal.

In an embodiment, the ion(s) doped in the crystal is/ are selected from the group comprising Praseodymium (Pr), Neodymium (Nd), Europium (Eu), Erbium (Er), Thulium (Tm), Ytterbium (Yb). Preferably, the ion(s) is/are Tm^{3+}. In an embodiment, the crystal is selected from the group comprising lanthanum fluoride (LaF_3), Yttrium orthosiliate (Y,SiO_5), Yttrium (III) Vanadate (YVO_4), Yttrium-Aluminium-Garnet (YAG). The apparatus may be configured to burn the spectral hole(s) into the rare-earth crystal before the modulated beam is passed through the crystal. Alternatively, the apparatus may be configured such that the spectral hole(s) is/ are burnt into the rare-earth crystal concurrently with the modulated beam being passed through the crystal.

In the case of a rare-earth doped crystal, the transmitted beam may have a wavelength substantially the same as a resonance in the resonant medium. In the case of Tm^{3+} ions doped in a YAG crystal, the transmitted beam may have a wavelength of about 793.38 nm. The frequency of the beam may be about 30 GHz.

The apparatus may comprise a cryostat to holding the resonant medium at a cryogenic temperature, such as about 4K. The temperature may be less than about 10 K. In the case of Tm^{3+} ions doped in YAG, the temperature may be less than about 3 K.

In an embodiment, the apparatus comprises a frequency stabilisation system to perform frequency stabilisation on a laser beam that is transmitted to the vibrating subject from a laser source. The frequency stabilisation system may provide a combination of optical and electronic feedback to the laser source. The frequency stabilisation system may be configured to use part of the beam that has passed through the resonant medium for optical feedback and part of the beam that has passed through the resonant medium for electronic feedback. The frequency stabilisation system may be configured to deliver a part of the beam that has passed through the resonant medium to a detector, to determine the frequency difference between the laser beam and a spectral hole in the resonant medium and from the frequency difference, to adjust the laser beam frequency substantially to the centre of the spectral hole. The frequency stabilisation system may be configured to deliver a part of the beam that has passed through the resonant medium back into the laser source to provide optical feedback to the laser source.

In an alternative embodiment, the resonant medium comprises a gas or vapour which is adapted to function as a sharp frequency discriminator. The apparatus may comprise a gas cell which contains the gas or vapour. In an embodiment, the resonant medium may comprise a molecular gas or an atomic vapour. In an embodiment, the gas or vapour comprises an alkali metal vapour. In an embodiment, the gas or vapour is selected from the group comprising lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb), iodine, ammonia, acetylene, Cesium (Cs).

The apparatus may be configured to pass a signal from a coupling beam and the modulated beam, into the gas or vapour. The coupling beam and the modulated beam may be detuned away from a doppler broadened transition of the gas or vapour, to make use of offresonant Raman transitions. The apparatus may be configured to pass the coupling beam and the modulated beam through a polarising beam splitter and to direct the signal that is output from the beam splitter into the gas or vapour. The apparatus may be adapted to generate the coupling beam from the transmitter.

The gas or vapour may be at ambient or room temperature (about 20°C to about 25"C). When an atomic vapour is used, the vapour may be between room temperature and about 150°C.
The modulated beam may be a phase modulated beam.

Where specific integers are mentioned herein which have known equivalents in the art to which this invention relates, such known equivalents are deemed to be incorporated herein as if individually set forth.

As used herein the term "(s)" following a noun means the plural and/or singular form of that noun.

As used herein the term "and/or" means "and" or "or", or where the context allows both.

The invention consists in the foregoing and also envisages constructions of which the following gives examples only.

Description of drawings

The present invention will now be described, by way of non-limiting example, with reference to the accompanying drawings in which:

FIGURE 1 shows a schematic of an apparatus in accordance with an embodiment of the present invention that uses a resonant medium to detect ultrasound;

FIGURE 2 shows the spectrum of a beam before and after interacting with a vibrating subject;

FIGURE 3 shows a phasor diagram of the modulation and carrier frequency components;

FIGURE 4 shows the energy level diagram of Tm^{3+} ions in Tm:YAG;

FIGURE 5 shows the amplitude and phase response of a spectral hole;

FIGURE 6 shows the amplitude and phase response of an optimal spectral hole;

FIGURE 7 shows an apparatus setup in accordance with a first embodiment of the present invention, which uses rare-earth material as resonant medium;

FIGURE 8 shows the homodyne signal processing elements of the apparatus of FIGURE 7;

FIGURE 9 shows an embodiment of a laser stabilisation setup;

FIGURE 10 shows the beat spectra of two identically locked laser beams;

FIGURE 11 shows the ultrasound detection signal from the apparatus of FIGURE 7;

FIGURE 12 shows the ultrasound pulse detection from the apparatus of FIGURE 7;

FIGURE 13 shows the energy level diagram for Raman transitions;

FIGURE 14 shows an alternate energy level diagram for Raman transitions;

FIGURE 15 shows the calculated linear susceptibility for a probe field;

FIGURE 16 shows an apparatus setup in accordance with a second embodiment of the present invention, which uses Raman gas as resonant medium;

FIGURE 17 shows a detailed alternate apparatus setup in accordance with a second embodiment of the present invention, which uses Raman gas as resonant medium;

FIGURE 18 shows the results that have been obtained using the apparatus setup of FIGURE 17; and

FIGURE 19 shows the measured EIA profile 1901 and the calculated Kramers-Kronig relations.

Detailed description of embodiments of the invention

The present invention makes use of the spectral properties of a resonant medium to introduce a frequency dependent phase shift on a field to provide an amplitude modulated signal, where the modulation frequency of the amplitude modulation signal corresponds to ultrasound vibrations of a sample. The modulation frequency is easily detectable using a detector, such as a photodetector for example.

Embodiments of the present invention provide a method and an apparatus for detecting ultrasound vibrations of a subject. A beam that interacts with a vibrating subject is passed through a resonant medium. The beam may be reflected off a vibrating subject. Alternatively, the beam may have passed through a vibrating subject. The resonant medium is adapted to impart a 90° phase shift on the carrier frequency component of the reflected beam, while passing at least two major sideband frequency components, preferably with zero or minimal attenuation and without imparting any phase shift on the major sideband frequency components. Preferably, the resonant medium passes the carrier frequency component with zero or minimal attenuation, while imparting the 90° phase shift on the carrier frequency component. The resonant medium outputs an amplitude modulated signal. The ultrasound vibrations can be subsequently detected from the amplitude modulated signal.

In the various embodiments described below, same drawing reference numerals are used to indicate like parts between the different embodiments.

<u>Ultrasonic modulation of light</u>

A schematic of an optical system 1 in accordance with an embodiment of the present invention is shown in Figure 2. In general, a subject 5 of interest is illuminated while excited with ultrasonic waves. A transmitter 3, which in an embodiment is a laser source, emits a beam of light 4 described by the electric field E_m towards a vibrating subject 5. The beam 4 is reflected off or travels through the surface of the subject 5 vibrating at an angular frequency ω_m in the ultrasonic frequency regime. A portion of the beam 4 becomes phase modulated, producing sidebands separated from the carrier by the ultrasonic frequency, and the mean phase of these two sidebands is 90° out of phase with the unmodulated carrier portion. It will be understood that the carrier and the sideband have different frequencies and so move in and out of phase with one another as time progresses. However, the phase modulation of the carrier is 90 degrees different to the mean phase of the two sidebands.

The sidebands carry useful information about the properties of subject 5, while the carrier portion contributes to noise. Electric field E_{refl} is the phase modulated beam 6 reflected off the vibrating subject or surface 5. The beam 6 is then directed through a resonant medium 7 where the phase modulation in the beam 6 is converted to amplitude modulation. The signal 8 emitting from the resonant medium 7 is detected using a detection apparatus 2. The detection apparatus 2 comprises a photodetector 11, which converts the detected signal into a photocurrent, I_{Sig}. Homodyne signal processing using a local oscillator generator 9, mixer 13 and low pass filter 15 is used to produce a measurable signal 10 representing the ultrasonic vibrations of the subject 5.

The beam 4 is emitted by the laser source 3 at an angular frequency ω_c given by its wave vector k and the speed of light c:

$$\omega_c = c \times k \qquad \text{Equation 1}$$

The wavelength of the beam 4 is the same as, or close to, a resonance in the resonant medium 7. The frequency of the beam 4 is within the sample dependent linewidth of the resonant medium 7. The beam 4 has a wavelength close to a narrow peak in the resonant medium's 7 absorption spectrum. Preferably, the peak is less than about 2 nm wide. Preferably, the wavelength of the beam 4 is closer to a centre of the peak than about twenty times the full-width half-maximum width of the peak. For the second embodiment described below that uses Raman features, the wavelength of the beam is preferably closer to a centre of the peak than about forty times the full-width half-maximum width of the peak.

The beam 4 emitted by the laser source 3 has an instantaneous electric field $E_{in}(t)$ at some point of time t given by

$$E_{in}(\mathrm{i}) = \text{¾e}\{\tilde{E}_0 \exp(i\omega_c t)\} \qquad \text{Equation 2}$$

Where t is time and $\tilde{\boldsymbol{E}}_0$ is the phasor describing the electric field at t = 0, given by

$$\tilde{E}_0 = |E_0| \exp(i\phi) \qquad \text{Equation 3}$$

where ϕ is the static phase of the field. Assuming that the detection time-scale is much longer than the frequency of the beam 4, the intensity of the beam 4 emitted by the laser I_{in} is given by

$$I_{in} = I_0 = \frac{c\epsilon_0 n}{2}|E_{refl}(t)|^2 \qquad \text{Equation 4}$$

$$= \frac{c\epsilon_0 n}{2}[\Re e\{\tilde{E}_0 \exp(i\omega_c t)\}]^2$$

$$= \frac{c\epsilon_0 n}{2}\tilde{E}_0^{\,*}\tilde{E}_0 \qquad \text{Equation 5}$$

where ε_0 is the permittivity of free space and n is the refractive index of free space. I_{in} is identical to the intensity I_0 at t = 0, so long as no appreciable attenuation of the beam 4 occurs.

When the beam 4 impinges the vibrating surface 5, the beam 4 scatters off the vibrating surface 5 with a displacement of U (the amplitude of ultrasonic modulation). If the vibration is acoustic and of single frequency, the electric field of the beam 4 becomes a phase modulated signal 6 and can be characterised by the modulation depth M. The modulation depth M describes the amount of phase shift imparted on the reflected beam 6, and is given by:

$$M = \frac{4\pi U}{\lambda} \qquad \text{Equation 6}$$

Hence, the resultant reflected field E_{refl} 6 can be written as

$$E_{refl}(t) = \Re e\{\tilde{E}_0 \exp(i\omega_c t)\exp(-iM\cos[\omega_m t])\} \qquad \text{Equation 7}$$

A Bessel series expansion can be used to decompose the cosine term in Equation 6, which gives:

$$E_{refl}(t) = \Re e\left\{\tilde{E}_0 \exp(i\omega_c t)\sum_{n=-\infty}^{\infty} i^n J_n(M)\exp(in\omega_m t)\right\} \qquad \text{Equation 8}$$

where $J_n(M)$ is the n^{th} Bessel function of the first kind with argument M.

The reflected electric field 6 can be considered to be a collection of Bessel waves with independent amplitude, frequency and phase, propagating through free space. Therefore, the effect of the light propagating through an optical system with a frequency dependent amplitude or phase response can be determined by performing appropriate transformations on each independent wave. The resultant field can be calculated as the sum of the wave components. In most cases, the ultrasonic displacement is small such that $M \leq 1$.

Jo(M) is representative of the carrier component of the phase modulated signal 6. The first order terms $J_{\pm 1}(M)$ and $J_{-1}(M)$ are representative of the first order or major sidebands of the phase modulated signal 6.

Assuming that $J_0(M) \approx 1$ and $J_{\pm 1}(M) \sim \pm M$, Equation 8 can be simplified by discarding all but the first order terms of the sum

$$E_{ref}(t) = \Re e\{\tilde{E}_0 \exp(i\omega_c t)[iM \exp(i\omega_m t) + 1 + iM \exp(-i\omega_m t)]\} \quad \text{Equation 9}$$

As shown in Figure 2, light 6 reflected off a vibrating mirror 5 becomes phase modulated at the ultrasound frequency due to Doppler shift from the moving surface. The spectrum of the phase modulated signal comprises the unmodulated carrier frequency ω_c and sideband frequencies $\omega_c \pm \omega_m$. The ultrasound frequency ω_m corresponds to the difference between the unmodulated frequency ω_c and one of the sideband frequencies $\omega_c \pm \omega_m$. The challenge in performing ultrasound detection arises from the fact that the modulated portion of light is small (the modulation index is typically a few percent of the unmodulated portion) as well as being close in frequency to the unmodulated carrier frequency.

The resultant electric field 6 comprises three waves having angular frequencies of ω_c (the carrier angular frequency) and $\omega_c \pm \omega_m$ (the major sideband angular frequencies). From this expression, the amplitude of the sidebands are direcdy proportional to M. Flowever, the amplitude of the sidebands is encoded in the phase of the field 6. A phase sensitive measurement needs to be carried out to detect the amplitude of the sidebands. Several methods exist that enable the amplitude of the sidebands to be measured. The most common methods use a phase discriniinator, such as an interferometer. However, as mentioned above, these methods suffer from limited etendue due to the mode-matching and optical requirements of the setup.

Figure 3 shows the phasor diagram of the unmodulated frequency ω_c component and the modulation frequency component ω_m. Referring to Figure 3(1), the phase modulation of a carrier with frequency ω_c with a modulation frequency of ω_m results in sidebands generated at $\omega_c \pm \omega_m$ with a phase difference of 90° relative to the carrier. The two sideband phasors $\omega_c \pm \omega_m$ rotate in opposite directions relative to one another and there will be no net change in length of the phasor of the carrier. Therefore, no amplitude modulation of the carrier is observed. Referring to Figure 3(11), by using the phase response of a resonant medium, the phase of the carrier can be shifted relative to the sidebands(for example by 90°), such that the sidebands now interfere and beat against the carrier, thereby producing a detectable amplitude modulation. The frequency of this beat modulation ω_m is the difference in frequency between the sidebands and the carrier. The beat modulation frequency ω_m corresponds to the ultrasound frequency.

Embodiment 1: Using rare-earth ion doped material as resonant medium

In a first embodiment, the present invention comprises a method for detecting ultrasound comprising passing a phase modulated beam 6 that has interacted with a vibrating subject 5 through a resonant medium 7 wherein the beam 6 has a carrier frequency component and two major sideband frequency components. The resonant medium 7 imparts a phase shift on the carrier frequency component and passes the two major sideband frequency components preferably with zero or rrdnimal attenuation to output an amplitude modulated signal 8. In particular, the resonant medium 7 imparts a phase shift of substantially 90° on the carrier frequency component of the phase modulated beam 6 to convert the phase modulated beam 6 into an amplitude modulated signal 8. The ultrasound vibrations of the subject 5 can be detected from the amplitude modulated signal 8.

In this embodiment, the resonant medium 7 comprises a rare-earth ion doped crystal, and the method comprises spectrally burning at least one hole in the crystal. Preferably, the rare-earth ion doped crystal comprises Tm^{3+} ions doped in a Yttrium-Aluminium-Garnet (YAG) crystal. Preferably, the spectral hole(s) is/are burnt into the rare-earth crystal before the phase modulated beam 6 is passed through the crystal. Alternatively, the spectral hole(s) is/are burnt into the rare-earth crystal concurrendy as the phase modulated beam 6 is passed through the crystal.

Preferably, the transmitted beam 4 has a wavelength substantially the same as a resonance in the resonant medium 7. Preferably, in the case of Tm^{3+} ions doped in a YAG crystal, the transmitted beam 4 has a wavelength of about 793.3 nm, and preferably about 793.38 nm, and a frequency is somewhere in the frequency range where the Tm ions absorb. The width of this region is somewhat crystal dependent and is 30 GHz wide in the crystal used here.

Preferably, the ion(s) is/are selected from the group comprising Praseodymium (Pr), Neodymium (Nd), Europium (Eu), Erbium (Er), Thulium (Tm), Ytterbium (Yb). Preferably, the ion(s) is/are Tm^{3+}. Preferably, the crystal is selected from the group comprising lanthanum fluoride (LaF_3), Yttrium orthosiliate ($Y,Si0_5$), Yttrium (III) Vanadate ($YV0_4$), Yttrium-Aluminium-Garnet (YAG). Preferably, the resonant medium comprises Tm^{3+} ions doped in a YAG crystal.

Preferably, the method comprises holding the resonant medium at a cryogenic temperature, such as about 4K for example. The apparatus will preferably have a cryostat for that purpose. The temperature at which the resonant medium is held depends on the system. Preferably, the temperature is less than 10K to avoid phonon induced dephasing. In the case of Tm^{3+} ions doped in a YAG crystal, the temperature is less than about 3K

The first embodiment also describes a suitable apparatus for performing the method.

<u>Spectral hole-burning</u>

To understand the optical effects introduced by a rare-earth ion doped crystal, consider the crystal as a simple collection of ions. If left alone, these ions will reside in a state where the ions have the lowest energy (a ground state). However, if a photon with a wavelength corresponding to an atomic transition impinges on an ion, the photon is absorbed and the ion will be excited to a higher energy state (an excited state). This ion remains in the excited state for some time before spontaneously decaying into a lower energy state by emitting a photon. The average time required for the ion to decay to the ground state(the lifetime) can be determined by considering the statistics from a collection of such ions.

In this embodiment, the rare-earth ion doped crystal comprises Tm^{3+} ions doped in a Yttrium-Aluminium-Garnet (YAG) crystal.

Referring to the energy level diagram shown in Figure 4, the ions can be thought of as a simple two level system having a transition between the $^3H_6$ ground state to the $^3H_4$ excited state with a $^3F_4$ metastable state.

The metastable state $^3F4$ is due to a transition from the $^3H_6$ ground state to the $^3H_4$ excited state 21 being only weakly allowed. The $^3H_6$ ground state to $^3H_4$ excited state transition has a transitional wavelength λ_{13} of 793.38 nm. The $^3H_4$ excited state is relatively short-lived with a lifetime τ_{12} of about 0.5 ms, after which the ions decay to the $^3F_4$ metastable state, which has a lifetime $\tau_{23}$of about 12.5 ms. Due to the long-lived $^3F_4$ metastable state, it is possible to manipulate the population of ions in the $^3H_6$ ground state by optical pumping. Consider a collection of Tm^{3+} ions in the ¾ ground state. If light with the same transitional wavelength of the $^3H_6$ ground state to $^3H_4$ excited state, that is 793.38 nm is incident on the ions, the ions will be excited into the $^3H_4$ excited state and eventually the $^3F_4$ metastable state becomes filled. As the ions are pumped away from the ground state $^3H_6$, there will be no ions left to interact with the light which causes an increase in intensity of transmitted light. Hence, spectral features lasting tens of milliseconds can be created by this process known as "spectral hole burning".

Flowever, not all ions have exactly the same transition frequency due to inhomogeneous broadening effects such as Doppler or Stark shifts. Therefore, if one were to burn a hole in the rare-earth ion doped crystal, then scan the frequency of the laser, the transmission of the laser will increase around the region of the spectral hole, but will be attenuated elsewhere depending on the inhomogeneous absorption profile of the ions.

Figure 5 shows the amplitude (I) and phase (II) response of a spectral hole with linewidth Γ and in a sample with absorption coefficient α. The hole has a linewidth of around 200 kHz and a maximum phase shift of about 2.7°.

The absorption coefficient a describes the amount of maximum absorption of light. The linewidth Γ is the half-width at half-maximum of the transmission. The Hnewidth Γ is dependent on the stability of the burning laser frequency and is limited due to homogeneous broadening effects in the crystal.

A spectral hole, like any narrow filter, will necessarily, also be dispersive. This is stated mathematically by the Kramers-Kronig relations, which are a direct result of causality. For example the spectral hole with transmission spectrum shown in Figure 5(1) will necessarily have a phase response as shown in Figure 5(11).

Plence, light with a frequency close to the center of the hole will have its phase shifted compared to light with frequencies away from the hole or light with a frequency corresponding exactly to the center of the hole, as shown in Figure 5(11).

In one embodiment, the resonant medium 7 comprises a rare-earth ion doped crystal, and the method comprises spectrally hole burning a hole in the crystal.- Preferably, the hole is slightly offset from the carrier frequency component of the phase modulated beam 6. Preferably, the hole is near the carrier frequency component and has relatively wide trenches either side to allow the major sideband frequency components through without any attenuation or phase shift. Alternatively, the hole may have an edge near the carrier frequency component of the phase modulated beam 6 and may have relatively wide trenches either side to allow the major sideband frequency components through without any attenuation or phase shift. Alternatively, the resonant medium 7 comprises a rare-earth ion doped crystal, in which more than one hole has been spectrally burned.

The phase shift imparted by the crystal provides a means to convert the phase modulation of the ultrasonically modulated light into amplitude modulation.

The linear complex transfer function T(ω) given by for a spectral hole can be modelled by

$$T(\omega) = \exp\left[-\frac{\alpha}{2}\left(\frac{i(\omega_H - \omega)}{\frac{\Gamma}{2\pi} + i(\omega_H - \omega)}\right)\right]$$ Equation 10

where Γ is the hole Hnewidth, a is the absorption coefficient, ω_H is the hole frequency, and ω is the angular frequency of the light propagating through the sample. The transmission of light is given by $|T|^2 = T(\omega)^* T(\omega)$ and the phase shift imparted is given by the angle of T in the complex plane.

Equation 8 can be rewritten as

$$E_{fiu} = \tilde{E}_0 \exp(i\omega_c t) \sum_{n=-\infty}^{\infty} i^n T(\omega_n) J_n(M) \exp(in\omega_m t)$$

Equation 11

As the effects of the spectral hole are frequency dependent, the appropriate transfer function are multiplied to the individual terms in Equation 9 to obtain an expression for the reflected field after propagation through the crystal given by

$$E_{fin}(t) = \Re e\{\tilde{E}_0[iT(\omega_m)M\exp(i\omega_m t) + T(0) + iT(-\omega_m)M\exp(-i\omega_m t)]\}$$ Equation 12

The intensity of this field I_{fijt} is given by

$$I_{fit} = \frac{c\epsilon_0 n}{2}\frac{|\tilde{E}_0|^2}{2}\{(T(\omega_m)M\exp(tw_m t) + T(0) + T(-\omega_m)M\exp(-i\omega_m t))\ \text{x e.e.}\}$$ Equation 13

Where $\left|\tilde{E}_0\right|^2 = \tilde{E}_0^* \tilde{E}_0$, IQ is given by Equation 4 and c.c. is complex conjugate of the terms in the square brackets in Equation 12.

As we are operating in the small displacement limit $M \leq 1$, we can expand this equation and disregard terms which have a factor of M^2 to obtain

$$I_{fib} = \frac{c\epsilon_0 n}{2}\frac{|\tilde{E}_0|^2}{2}\{T(0)^*T(0) + iM\beta\exp(i\omega_m t) - iMi''\exp(-i\omega_m t)\}$$ Equation 14

where β is a complex term defined as,

$$\beta = T(\omega_{m}) T(0)^{*} - T(-\omega_{m})^{*} T(Q)$$ Equation 15

We can simplify Equation 14 by expanding the complex exponentials to get

$$\begin{aligned} I_{filt} &= \frac{c\epsilon_0 n}{2}\frac{|\tilde{E}_0|^2}{2} \times \{T(0)^{*} T(0) + iM(\beta - \beta^{*})\cos(\omega_m t) - M(\beta + \beta^{*})\sin(\omega_m t)\} \\ &= \frac{c\epsilon_0 n}{2}\frac{|\tilde{E}_0|^2}{2} \times \{T(0)^{*} T(0) - 2M\,\Im(\beta)\cos(\omega_m t) - 2M\,\Re(\beta)\sin(\omega_m t)\}. \end{aligned}$$

Equation 16

Detection

The embodiment of the detection method and system described below can also be used for the second embodiment of the invention.

In an embodiment, the amplitude modulated signal from the resonant medium comprises a carrier signal component with an amplitude that is modulated by a modulation signal having a modulation frequency, wherein the modulation frequency is proportional to the vibrations of the subject. Preferably, the modulation frequency is proportional to the difference between the carrier frequency of the phase modulated signal and one of the two major sideband frequency components. In a preferred embodiment, the step of detecting the ultrasound vibrations involves the step of detecting the modulation signal. Preferably, the modulation signal is detected using a homodyne apparatus. Alternatively, the modulation signal is detected using a heterodyne apparatus. Preferably, the modulation signal is detected using a digital signal processor.

From equation 16, the terms enclosed by square brackets are real, which shows that the intensity being detected is amplitude modulated. There are two terms which have an oscillating component that are 90° out of phase with each other. These terms are directly related to the real and imaginary quadratures of β. The light impinging on the detector 11 is converted into a photocurrent I'_{Sig} that is related to the intensity of the light by conversion constants, giving

$$I'_{Sig} = I'_0 \left[\Gamma(0)^* \Gamma(0) + 2M \Im m(\beta) \cos(\omega_m t) - 2M \Re e(\beta) \sin(\omega_m t) \right]$$ Equation 17

where Γ_0 is given by

$$I'_0 = \frac{\eta q}{hv} I_0,$$ Equation 18

where η is the quantum efficiency of the detector, q is the charge on an electron and hv is the energy of the photons arriving at the detector.

To isolate the quadratures of the field, homodyne signal processing is performed on the detected signal. As shown in Figure 1, I_{Sig} is mixed with a local oscillator (LO) 9, operating at the frequency of modulation, which is known a priori. Assuming that we choose a LO = $\cos(\omega_M t)$, we obtain for the signal after the mixer 13,

$$\begin{aligned} I_{Sig} &= \frac{c\epsilon_0 n}{2} |\tilde{E}_0|^2 (T(0)^* T(0) \cos(\omega_m t) - 2M \Im m(\beta) \cos^2(\omega_m t) - 2M \Re e(\beta) \sin(\omega_m t)) \cos(\omega_m t) \\ &= I_0 \times [T(0)^* T(0) \cos(\omega_m t) - 2M \Re e(\beta) \sin(\omega_m t)) \cos(\omega_m t) - 2M \Im m(\beta)(1 - \cos(2\omega_m t))] \end{aligned}$$ Equation 19

The signal is then low pass filtered 15 to obtain the zero frequency (DC) components, given by

$$\begin{aligned} I_{Sig} &= -\frac{c\epsilon_0 n}{2} |\tilde{E}_0|^2 2M \Im m(\beta) \\ &= -2I_0 M \Im m(\beta) \end{aligned}$$ Equation 20

Alternatively, if we chose a LO = $\sin(\omega_M t)$, we get the real quadrature instead, given by

$$I_{Sig} = -2I_0 M \Re e(\beta)$$ Equation 21

Therefore, ultrasonic modulation can be remotely detected using a resonant medium which in the first embodiment comprises a rare-earth ion doped crystal 7. Furthermore, the modulation depth M can be directly measured from the detected light intensity by performing homodyne detection.

Noise and sensitivity limits

The following also applies to the second embodiment of the invention described below that uses Raman features.

So far we have considered the case for a noiseless detection system. It is useful to obtain a figure of merit of the accuracy of the detection system. We can do this by assuming that shot noise is the dominant noise source in our system. The variance due to shot noise (SN) is given by

$$\sigma(SN) = \sqrt{2\hbar\omega_c \overline{P} f_B}$$ Equation 22

where h is Plank's constant, P is the time-averaged power arriving at the detector and f_B is the bandwidth of the detection. If the definition of M in Equation 6 is substituted into Equation 20, the corresponding amplitude of the error signal is given by,

$$I_{Sig} = 2I_0 \left(\frac{4\pi U}{\lambda}\right) \Im m(\beta)$$ Equation 23

which are dependent on the ultrasonic displacement.

Hence a sensitivity S can be defined as,

$$S = \frac{I_{Sig}}{U} = 2 I_0 \left(\frac{4\pi}{\lambda}\right) \Im m(\beta)$$ Equation 24

The sensitivity S, which has units of W m^{-1}, provides a relationship between the received intensity and the ultrasonic displacement. An equivalent position noise σ_{disp} from the shot noise can be defined as,

$$\sigma_{disp} = \frac{\sigma_{SN}}{S}$$

$$= \frac{\lambda\sqrt{2\hbar\omega_c P f_B}}{8\pi I_0 \Im\mathrm{m}(\beta)} \qquad \text{Equation 25}$$

$$= \frac{\lambda\sqrt{2\hbar\omega_c f_B}}{8\pi \sqrt{I_0} \Im\mathrm{m}(\beta)} \qquad \text{Equation 26}$$

which has units of $m\sqrt{Hz}\sqrt{W}^{-1}$.

The same analysis for the other quadrature can be performed using Equation 21 to get

$$\sigma_{disp} = \frac{\lambda\sqrt{2\hbar\omega_c f_B}}{8\pi \sqrt{I_0} \Re\mathrm{e}(\beta)} \qquad \text{Equation 27}$$

Optimal spectralfeature

A model of the spectral hole used in the experiments is shown in Figure 5. However, this spectral feature is not ideal as the maximum phase shift of the carrier is around 2.7°. One way of improving the phase shift on the carrier is to make the sample more optically thick, however this would cause more attenuation of the sidebands.

The amplitude and phase response of a spectral feature that is close to optimal operation is shown in Figure 6. This spectral feature is close to optimal as it produces a phase shift of 90° of the carrier - frequency component with no attenuation of the major sidebands. Figure 6(1) shows the transmission of the spectral feature as a function of frequency offset from the hole frequency. Figure 6(11) shows the phase shift generated. Figure 6(111) shows a *view* of the feature about zero offset frequency. Figure 6(IV) shows the phase response of the spectral feature about zero offset frequency.

The transmission of the spectral feature is shown in Figure 6(1) with a closeup shown in subplot (III). The phase response of the hole is shown in subplots (II) and (TV). Such a spectral feature would be made by starting with a flat inhomogeneous broadening profile and optically pumping away ions in the regions in where transparency is desired. It can be seen that this spectral feature has high transmission for both the carrier and the sidebands, while the steep dispersion due to the sharp edge of the narrow absorptive feature near the carrier frequency imparts the desired 90° phase shift on the carrier frequency component.

Experimental set-up and results

A schematic of the experimental setup is shown in Figure 7. The experimental setup comprises a Polarizing Beam Splitter (PBS) 61, Beam Pickoff (BPO) 62a-b with 10% reflectivity, Electro-Optic Modulator (EOM) 63a-b (New Focus 4002), half-wave plate ($\lambda/2$) 64, optical isolator 67, Acousto-Optic Modulator (AOM) 65a-b, Plano-convex lenses with focal lengths (L1-L4) 100mm, 500mm, 200mm and 50mm respectively 66a-d, and Photpdiode Detector (Det) 2a-b.

The AOM 65a is operated at 80 MHz, while for burning sequences AOM 65b is operated at -90 MHz. This gives a 10 MHz offset from the laser wavelength. AOM 90 is also switched to perform the probe pulse at 90.039 MHz.

Laser source

The beam from the laser source 3 is split into two paths at the first pickoff (BPO) 62a after the optical isolator 67. The beam following the path 69a is used to stabilise the laser frequency, while the path 69b indicates the experimental arm of the setup. The laser source 3 uses an Eagleyard diode operating at approximately 793.38 nm in a Littrow configuration with a free running linewidth of over 4 MHz. The diode used is a EYP-RWP-0840-06010-1500-SOT02-0000 from Eagleyard photonics, with the center of its gain peak around 840 nm. The laser can be tuned to a desired wavelength with a diffraction grating. Current for the diode is provided by a current source built to the design of Libbrecht and Hall (1993), but modified to allow a larger current to be supplied. Frequency stabilization of the laser is achieved using a hybrid technique which incorporates Pound-Drever-Hall (PDH) electronic locking with an optical feedback loop. As a frequency reference for the PDFI lock, a spectral hole is burnt in the sample by the beam following the path 69a. The transmitted light is detected by a photodetector 2a and is used to generate an error signal which controls laser frequency via the laser current. This eliminates most low frequency noise on the laser and brings the laser linewidth down to 2 MHz. Some of the transmitted light is fed back into the laser source to provide optical feedback. It was found that the optical feedback eliminated most of the high frequency noise, giving a laser linewidth of around 200 kHz.

Experimental arm

The beam entering the experimental arm 69b of the setup has an input laser power of 2 mW and a spot size of 2 mm. The beam is directed through two acousto-optic modulators 65a-b (AOM 90 and AOM 80) as shown in Figure 7. The two AOMs 65a-b are operated at 80 MHz and -90 MHz, thereby giving a total laser frequency shift of 10 MHz. This was done to provide a frequency difference between the beams used for laser locking and for experiments. The AOMs 65a-b are controlled using a computer, allowing the frequency of the beam to be changed, ramped or the beam can be switched off completely. This control is achieved by changing the input frequency to AOM 90 65b. AOM 65a is operated at 80 MHz throughout the experiment. The overall efficiency of the AOMs 65a-b is about 55% each, giving a total power of 0.6 mW incident on the sample. The sample 7a used in the setup is a 0.1% doped Tm:YAG (Scientific Materials) and dimensions 8x4x4 mm. The crystal 7a is cooled to a temperature of 4 K using a cryostat refrigerator (Cryomech). To ensure that the locking beam does not burn unwanted holes, the setup is aKgned so the beams do not overlap on the crystal 7a. Ultrasonic modulation of the beam is generated using either an electro-optic modulator 63b (EOM 2) or a piezoelectric transducer 5 (PZT), mounted onto the back of a mirror. In the commercial embodiment, the subject will be in the position of PZT 5. While the beam passes through both the EOM 2 63b and the PZT 5 throughout the experiment, only one is used to obtain a set of data. The driving signal that vibrates the PZT 5 is generated using a function generator (Stanford Research Systems) with a frequency of 1.11 MHz. The signal is then amplified using a research amplifier before being connected to the EOM 63b or PZT 5.

Detection

The light transmitted through the sample is detected using a photodetector 2b and demodulated using homodyne signal processing. To perform homodyne signal processing, we use the setup shown in the electrical block diagram in Figure 8.

Figure 8 shows the homodyne signal processing 70 elements. The diagram of processing block leading from photodetector 2b to the oscilloscope 78 is shown. Two data sets from the same detected signal are recorded; the AC-Coupled version is shown at the top of the diagram and the DC-Coupled version is shown at the bottom of the diagram. A DC block 72 consisting of a capacitor is used to filter DC components from the AC-Coupled signal, which is then subjected to homodyne detection with a components labelled BPF: DC-2.5MHz Bandpass Filter 75, LO Gen: SRS function generator 77 used to deliver a 5.96 dBm local oscillator at 1.11 MHz. The DC-Coupled signal is direcdy recorded onto an oscilloscope 78.

A DC block 72 was used to attenuate the components of the detected signal at zero frequency. This filtered signal was then amplified using two low noise amplifiers (Minicircuits ZFL-500 and ZFL-1000LN) 73, before being mixed at mixer 79 with a local oscillator (LO) signal at 5.96 dBm. The local oscillator signal is generated by a function generator 77 phase locked to the one used to generate the ultrasound to reduce inaccuracy due to fluctuations in the operating frequencies of the two function generators. The mixed signal is then amplified and low pass filtered by a preamplifier 76(Stanford Research Systems) and collected using an oscilloscope (Tektronix) 78. The DC coupled data is collected using a second channel of the same photodetector.

To demonstrate the ability of the method of the first embodiment to detect ultrasonic modulation, two experiments are performed: (i) the burn and sweep experiment demonstrates the detection of a constant ultrasound modulation by spectral hole burning; and (ii) the pulse experiment demonstrates the effectiveness of the first embodiment in detecting pulses of ultrasound.

Laser stabilisation arm

As the ultrasonic motion of the subject is encoded as phase modulation, any phase noise on the laser will appear as a false signal. This makes the use of low cost semiconductor laser systems problematic as they usually exhibit large amounts of phase noise. To achieve a laser with low phase noise, in an embodiment a hybrid approach is used which combines both optical feedback and electronic servo-control of the laser current.

Figure 9 shows the configuration of a preferred embodiment of the laser stabilisation system 80, that forms part of the whole system 60 shown in Figure 7. The laser stabilisation system 80 is shown separately in Figure 9 for clarity. The laser stabilisation system 80 is based on a diode laser 3 stabilised with a diffraction grating 3a in the Littrow configuration.

The light 69c leaves the laser source 3 and passes through a beam-splitter 61. The role of this beam splitter 61 is to provide a port where light can be fed back into the laser 3. The light then travels through an optical isolator 67, in this case a Faraday isolator (OFR IO-5-VNR-LP), to stop unwanted retro-reflected light from feeding back into the laser. It is preferable to modify this setup to use the polarizing beam splitter 62a at the exit of the Faraday isolator 67 to inject the light required for optical feedback. This has been implemented but the results shown here are taken with a separate beam-splitter.

A small part fraction (400 μW) 69a of the light exiting the Faraday isolator 67 is picked off the beam 69c and used to stabilize the laser source 3. This light first travels through an electro-optic-modulator 63a (New Focus 4002) which is driven with a 30 MHz sine wave at a level (10 dBm) to impart the beam 69c with approximately 10 degrees of 30 MHz phase modulation. The amount of phase modulation will vary as required. The frequency could be any value between about 10 MHz - and about 1000 MHz. This light is then passed through the Tm:YAG crystal 7a with doping concentration of 0.1% and dimensions 8x4x4 mm. Ideally, the carrier frequency component of the phase modulated signal burns a spectral hole into the crystal 7a but the phase modulated sidebands do not burn any holes in the crystal 7a (or at least burn shallower holes).

In order to have narrow holes, the intensity of light must be kept low. However in order to get a good signal to noise ratio for the error signal (described below), larger optical powers are desirable. For these reasons, it is desirable to have a large diameter beam hitting the Tm:YAG crystal 7a. For this reason, the beam is made as large as possible within the limitations of the 4 mm high Tm:YAG crystal.

After transiting the crystal 7a, a portion of the light 69d is directed toward a photo-diode based photodetector 2a. From the amplitude and phase of the signal on this at 30MHz it is possible to create a frequency error signal which gives the frequency difference between the laser beam and the spectral hole. This error signal is fed via a loop filter 603 to the current controller to servo the laser frequency to the centre of the hole.

Some of the light 69e that has been filtered by the spectral hole of the resonant medium 7a is injected back into the laser source 3. This provides optical feedback to the laser source 3 that is sharply peaked at the hole frequency, making the laser frequency much less sensitive to phase fluctuations due to the laser diode. The phase of this optical feedback light is not controlled in the experiment, and will vary as acoustic noise moves the positions of optics in the optical feedback loop. Small fluctuations in this phase about perfect positive feedback will cause the frequency to fluctuate about the centre of the hole, but this is corrected for by the electronic locking system 603.

To measure the stability of the setup, two identical lasers were stabilised using beams going through different positions of the Tm:YAG crystal. The spectra of the beat notes are shown (waveform 92) in Figure 10. When the optical locking for both lasers was disabled a large increase in the phase noise was observed (waveform 94).

(i) Experimental results - Burn and sweep

In order to demonstrate ultrasound detection, the sample 7a is prepared by burning a spectral hole. The modulated beam frequency is then swept across the range of the hole and the error signal is recorded. The hole was burnt by turning the laser on for 3 ms. Only 0.5 ms of burn time is shown in top section of Figure 11, sub figure S; the initial 2.5 ms is to the left of the axis in the figure. The laser frequency was then swept from -2 to +2 MHz over a period of 1 ms by scanning the input of AOM 90. Between subsequent shots, the laser source was turned off for 100 ms to enable excited ions to decay to the ground state.

Referring to Figure 11, an error signal is generated by ultrasonically modulated light passing through a Tm:YAG crystal. Subfigures M1-4show the ultrasound is generated by a PZT mounted to a mirror 5 at 1.11 MHz. The phase of the local oscillator is varied from 0-270° in 90° increments. Subfigures El-4show the light is modulated using an EOM 63a at 1.11 MHz. The phase of the local oscillator is also varied from 0-270° in 90° increments. The burn and sweep sequence is shown in subfigure S. The laser source is turned on for 3 ms (again 2.5 ms of the 3 ms burn time is to the left of the axes in the subfigure) in the burning phase, then its frequency swept over 4 MFIz in 1 ms. The laser source is turned off between shots, indicated by the dashed line.

The sequence used for a single shot is shown in Figure H(S). The error signal was derived through post processing of the detected signal as described previously. Traces of the error signal intensity as a function of laser beam frequency are shown in Figure 11 for modulation using the EOM (plots E1-E3) and the PZT driven mirror (M1-M4). The plots were obtained for LO phase ranging from 0° to 270° in 90° increments. Note that spikes in the signal are seen at t = Θ and 1 ms corresponding to discontinuities in the frequency probe sequence. To obtain a measure of the ultrasound, we calculate the modulation index M of the PZT driven mirror by calibrating the data using the known modulation index of the EOM. By dividing Equations 18 and 19 with I_0, the DC component of the recorded signal, the following equation can be obtained:

$$\frac{I_{Sig}}{I_0} = 2MG\Im m(\beta) \quad \text{or}$$
$$= -2M\Re e(\beta),$$

Equation 28

where we have included gain on the AC level of the signal G and the value I_{sig}/I_0 in practice is obtained by dividing the measured AC signal with the corresponding DC signal. The value of M can then be obtained by fitting the amplitude of the recorded data with the amplitude predicted by the theory. Doing this, we calculated an uncalibrated M for the EOM data of 36.06 rad. From the manufacturer's specifications, the modulation index of the EOM was calculated to be 240.9 mrad. Using Equation 23, we can then obtain a calibration factor of 0.2409/36.06 = 6.68×10^{-3}. This calibration factor is then used to calculate the M of the PZT driven mirror, shown in Table 1. From this we calculate an average modulation index of 14.6 mrad.

Run	*Fitted M (mrad)*
1	*15.9*
2	*11.8*
3	*11.9*
4	*18.7*

Table 1: Fitted values for the modulation index based on mirror data.

(ii) Experimental results - Pulses

A common use of ultrasonic detection is in the detection of ultrasound pulses. To demonstrate that the first embodiment method and apparatus are capable of detecting ultrasound pulses, the ultrasound modulator is driven using a sequence of pulses with varying length. To optimise the detected signal, the input sequence to AOM 90 is changed to burn a hole for 3 ms, then to shift the laser 39 kHz from the centre of the hole. The detected pulse sequence is shown in Figure 12 for LO phase varying from 0° to 270° in 90° increments as before. Referring now to Figure 12, signals are generated when pulses of ultrasound is turned on. Subfigures Ml -4 show the signal generated by PZT mounted to mirror, with phase of LO varying from 0-270° in 90° increments. Subfigures El-4 show the signal generated by EOM, with the same phase variation. The probe sequence used (waveform 102) is shown in subfigure P. The laser is turned on for 3 ms (2.5 ms of the burn time is to the left of the axis in the subfigure) to burn a spectral hole, then the laser frequency is set at 39 kHZ offset from the hole frequency. Pulses of ultrasound on the EOM or mirror are turned on (waveform 104). The laser is then turned off between shots.

For one quadrature, corresponding to Theta=90 or 270, the pulses are not detectable as expected. Note that the ultrasound pulses are of the same intensity, however the detected signal becomes weaker due to degradation of the spectral hole. The residual signal in the PZT driven mirror plots are due to stray pickup of the pulse signal.

Therefore, the apparatus and method of the first embodiment are capable of detecting both constant and pulsed modulation. While the system has been described as being used for detecting specular reflections off a mirror, it can also be used to detect diffuse signals.

Embodiment 2: Using Raman gas or vapour as resonant medium

The above describes one embodiment of the present invention that uses a rare-earth ion doped crystal as the resonant medium. The previous embodiment using rare-earth ion doped crystals as resonant medium uses the dispersive properties of a spectral hole to phase shift the unmodulated light so interference of the unmodulated light with the sidebands generates a detectable amplitude modulation signal. The dispersion due to a spectral filter can be used to shift the phase of the carrier thereby converting the phase to amplitude modulation. However, the invention can be realised using other resonant media. Rare-earth ion doped crystals are ideally suited for this method of detecting ultrasound in that the spectral responses can be made narrower than typical ultrasound frequencies. At the same time, the optical depths can be large enough to provide large enough phase shifts to efficiendy convert phase to amplitude modulation. A disadvantage of using rare-earth doped crystals in the detection of ultrasound is the requirement for cryogenic temperatures. While closed cycle coolers have improved gready in recent years, they will still represent the majority of weight, power consumption and cost of the detection system. It is therefore beneficial to look at other systems where narrow, optically thick resonances without the need for cryocooling can be found.

In solid state systems and liquids, the small quantum system quantum systems exhibiting the resonance are strongly perturbed by the movement of their neighbours. Rare earth ion dopants represent systems where these perturbations are particularly low; however, even in this situation they don't show the narrow resonances required until sufficiently low temperatures are reached.

The second embodiment demonstrates that ultrasound modulation can be detected using Raman absorption features, analogous to electromagnetically induced transparency (EIT), to generate a spectral filter. This allows us to perform the phase shift on the carrier signal, while not significandy attenuating the sidebands.

Dilute atomic vapours and molecular gases do not suffer nearly as greatly from such perturbations, and at low pressures the line widths are limited by the Doppler shift. Compared to ultrasonic frequencies these Doppler broadened widths are large $\approx 600\,MHz$ for the D lines of Rubidium at room temperature. This linewidth scales with the mass of the atom/molecule and the temperature as Sqrt[T/m].

An alternative way of achieving a Doppler free linewidth is using offresonant Raman transitions. In Raman spectroscopy two optical fields connect two low lying energy levels to the same upper state, as shown in Figure 13. This diagram shows two ground states 1301, 1302, and an excited state 1303. The excited state 1303 has angular momentum states larger or equal to that of the ground state 1301, 1302. An auxiliary coupling beam 1304 drives the transition from the ground state 1301 to 1303, while a weaker probe beam 1305 drives the transition from the ground state 1302 to the excited state 1303.

Figure 14 shows a more detailed energy level diagram. Consider a three-level energy system 1400 as shown in Figure 13. Figure 14 shows a three-level scheme for electromagnetically induced transparency (EIT) and electromagnetically induced absorption (EIA) in rubidium vapour. Ω_c denotes the coupling beam, Ω_p denotes the probe beam, Δ is the detuning of state |3> and δ is the detuning of the probe beam. The coherent spontaneous emission rate is given by γ.

System 1400 uses the D_1 transition hyperfine structure of Rb87, $5^2S_{1/2}$ (F-2) 1402 $\rightarrow$ $5^2P_{1/2}$ (F=1) 1404. The Raman absorption feature is generated using a process known as coherent population trapping. This process requires three states |1>, |2>, |3>, with the excited state |3> having possible angular momentum states larger or equal to that of the ground state |1>, |2>. An auxiliary coupling beam drives the 11> $\rightarrow$ |3> transition, while a weaker probe beam drives the |2> $\rightarrow$ |3> transition.

It is the probe beam that contains the phase modulation of interest and we are interested in the linear response of the atoms to this beam.

The Hamiltonian for a three-level atom is given by

$$H/h = *\Omega_p(\sigma_{13} - \sigma_{3_1}) + i\Omega_c(\sigma_{23} - \sigma_{32}) + \delta\sigma_{11} + \Delta\,\sigma_{33} + \text{Spontaenous emission terms} \qquad \text{Equation 29}$$

where σ_{nn} is the atomic population in state |n> and $\sigma_{n1}$is the atomic coherence of the transition between states |n> and |1>, Ω_c is the Rabi frequency of the transition between states |1> $\leftrightarrow$ |3>, Ω_p is the Rabi frequency of the transition between states |2> $\longleftrightarrow$ |3> and γ is the spontaneous emission term. Without loss of generality we have assumed the Rabi frequencies are real. The detuning of state |3> is given by Δ, while the detuning of the probe beam from state |2> is given by δ. Both these beams are detuned from one photon resonance but have small two photon detuning, that is Δ is large and δ is small. This means that both the coupling beam and the probe beam only interact significantly with the rubidium atoms when they are both present.

From this Hamiltonian, we can obtain the following quantum Langevin equations

$$\frac{d}{dt}\sigma_{13} = -(\gamma + i(\delta - \Delta))\sigma_{13} + \Omega_p(\sigma_{33} - \sigma_{11}) - \Omega_c\sigma_{12} + \text{noise terms}$$

$$\frac{d}{dt}\sigma_{12} = -i\delta\sigma_{12} + \Omega_c\sigma_{13} - \Omega_p\sigma_{32} + \text{noise terms}$$

Equation 30

We can simplify these equations based on the assumptions that the probe beam is weak (i.e. Ω_p is small), the atomic population will mostly be in state |1> and by dropping the noise terms.

This leads to
$$\frac{d}{dt}\sigma_{13} = -(\gamma + i(\delta - \Delta))\sigma_{13} - \Omega_p - \Omega_C\sigma_{12}$$

$$\frac{d}{dt}\sigma_{12} = -i\delta\sigma_{12} + \Omega_c\sigma_{13}$$

Equation 31

The steady state solution can be solved to give

$$\sigma_{13} \simeq \frac{-i\delta\Omega_p}{i\delta(i\delta + \gamma - i\Delta) + |\Omega_c|^2}$$

Equation 32

We can use the definition of the Rabi frequency, $\Omega_p = E d_{13} / \hbar$ and the complex susceptibility is given by $\chi = P / (\epsilon_0 E)$, where the polarisation of the gas is given by $P = N\, d_{13}\, \sigma_{13}$ and N is the number density of atoms, to obtain

$$\chi = \frac{iN|d_{13}|^2\delta}{\epsilon_0\hbar(\delta(i\delta + \gamma - i\Delta) - i|\Omega_c|^2)}$$

Equation 33

The transfer function for an electromagnetic field after travelling though a distance d is $T = \exp(i\chi d)$. Hence, the real part of χ determines the magnitude of phase shift imparted onto the light, and the imaginary part determines the loss.

Figure 15 shows the calculated linear susceptibility for the probe field. Parameters used were $\Delta = -500/(2\pi)$ MHz, $\gamma = 10/(2\pi)$ MHz and $\Omega_c = 1/(2\pi)$ MHz.

One can see that for large Δ the susceptibility (both real 901 and imaginary 903 parts) is small except for when $\delta\Delta = |\Omega_c|^2$ where the two terms in the denominator partly cancel and there is resonant enhancement of the susceptibility.

The absorption peak shown is very narrow. In reality, it will be somewhat larger due to a number of effects not taken into account in this simple model. These include dephasing mechanisms for the 1-2 transition, in particular, collisions, stray magnetic fields and transit time broadening. Doppler broadening of the $|1\rangle \rightarrow |2\rangle$ transition is important if the beams probe and coupling beams are not perfectly co-linear. Doppler shifts also cause inhomogeneity in Δ and this along with possible inhomogeneity in Ω_c causes different atoms to have different resonance frequencies, thus broadening the response of the ensemble.

The absorption features could be optimised beyond the 2 MHz width by using a vapour cell containing buffer gas which would exhibit less transit time broadening.

In the method and apparatus of the second embodiment of the invention, Raman transitions provide optical resonances narrower than Doppler widths via the use of an auxiliary "coupling" laser beam. In the second embodiment, the present invention comprises a method for detecting ultrasound comprising passing a phase modulated beam that has interacted with a vibrating subject through a resonant medium wherein the beam has a carrier frequency component and two major sideband frequency components, wherein the resonant medium imparts a phase shift on the carrier frequency component and passes the two major sideband frequency components with preferably zero or minimal attenuation to output an amplitude modulated signal; and detecting the ultrasound vibrations of the subject from the amplitude modulated signal. In particular, the resonant medium imparts a phase shift of substantially 90° on the carrier frequency component of the phase modulated beam to convert the phase modulated beam into an amplitude modulated signal. In this embodiment, the resonant medium comprises a gas or vapour which is adapted to be used as (or functions as) a sharp frequency discriminator. Preferably, the resonant medium comprises atomic vapour or molecular gases. Preferably, the gas or vapour is contained in a gas cell comprising

Rubidium (Rb) vapour. Preferably, the method comprises passing a coupling beam and the phase modulated beam through a polarising beam splitter and directing the signal that is output from the beam splitter into the gas or vapour. Preferably, the coupling beam is obtained from a beam that is transmitted to the subject. This embodiment also describes a suitable apparatus for performing the method.

Preferably, the transmitted beam has a wavelength substantially close to a resonance in the resonant medium.

The spectroscopic features of the gas or vapour are insensitive to temperature. The gas or vapour may be at ambient or room temperature (about 20°C to 25°C). In the case of atomic vapours, the cell is preferably heated to some temperature above room temperature but less than about 150°C in order to increase the vapour pressure and hence the amount of absorption.

Unless described below, the features and functionality can be considered the same as for the first (rare-earth) embodiment described above.

Experimental set-up and results

An embodiment apparatus for detecting ultrasound using Raman transitions is shown in Figure 16. This apparatus uses two states as the ground state with the same value for the absolute value of total atomic angular momentum *(F)* but different values for the component along the direction of the applied magnetic field (m_F) of ^{87}Rb.

Narrow absorbative features are produced in this setup. This has the benefit that the two photon detuning can be adjusted using a solenoid to tune the states using a magnetic field. This means that that the absorbative feature can be place in the optimal position with respect to the probe beam carrier frequency by simply tuning the magnetic field which is much simpler than adjusting the frequency of the laser.

Light beam from a laser source 3 is directed through a waveplate 81a and the polarising beam splitter 82a, in this manner two beams of opposite linear polarisation 83a-b are produced and by adjusting the waveplate 82 the amount of power in each beam 83a-b can be adjusted. One of these beams is the coupling beam 83a that is directed through the resonant medium 7b via a polarising beam splitter 82b. The polarising beam splitter 82b provides a convenient way to overlap both the coupling beam 83a and the probe beam 83b. The probe beam 83b is delivered through some deliver)' optics 84 to a small spot on the subject 5, the collection optics 85 then take the light reflected from this subject 5 and convert that into a beam which is then overlapped with the coupling beam 83a on the polarising beam splitter 82b before the Rb cell 7b. Overlapping the probe beam 83b and the coupling beam 83a does not affect the phase modulation on the probe beam 83b that passes through the resonant medium 7b.

As the light reaches the quarter waveplate 82b before the Rb atoms 7b it consists of the probe 83b and coupling light 83a in orthogonal linear polarisations. A correctly oriented quarter waveplate 81b converts these into left and right handed circular beams which then interact with the Rb atoms in the Rb cell 7b and the probe light 83b is affected by the Raman resonance. The quarter waveplate 81c after the sample reverses the effect of the first waveplate 81b and the probe 83b and coupling light 83a are then separated with a polarising beam splitter 82c. The probe beam 83b that is received from the vibrating subject 5 and delivered to the Rb cell 7b is phase modulated, having a dominant carrier component and sidebands. The probe beam has a carrier frequency component to be phase shifted and major sidebands, when the probe beam is delivered to the Rb cell with the coupling beam. The effect of the Raman resonance can be adjusted to convert the phase modulated probe light 83b into amplitude modulated light. The amplitude modulation on the probe light 83b is then detected with an intensity sensitive photodetector 2c such as a photodiode. A particular benefit of this method is that frequency of Raman feature is sensitive only to the frequency difference between the two beams, this means that much of the phase noise from the laser will not appear as a false signal on the detector 2c.

In operating the apparatus, the light/beam from the laser source 3 is detuned approximately 600 MHz to the red (lower frequency, longer wavelength) side of the Rb line. The probe beam 83b is at 1 μW and 3 mm in diameter, and the coupling beam 83a is at 60 mW and 20 mm in diameter. The use of a separate laser to optically pump atoms out of the ground state (not shown in Figure 16 but shown in Figure 17), will maximise depth of the absorption feature. The direction of the beam from that laser is not critical. With laser beams incident on the Rubidium atoms in this configuration the probe beam 83b will see and absorption feature of the order of 170 kHz wide, which is narrow compared to most ultrasound frequencies and therefore ideal for phase modulation to amplitude modulation conversion.

The frequency of the absorption for the probe beam 83b depends on both the separation between the ground states and via AC stark shifts the intensity of the coupling beam 83a and how far the laser is detuned from the line center. The use of solenoid 87 to apply an axial magnetic field can adjust the spacing between the two ground states. In this manner the magnetic field can be used to appropriately adjust the frequency difference between the carrier frequency component of the probe beam 83b and the peak of the Raman absorption to maximise detection sensitivity.

A detailed alternate embodiment apparatus for detecting ultrasound using Raman transitions is shown in Figure 17. The apparatus includes a control arm and a repump arm. Each arm comprises a laser source 3, 99 which provides a laser beam used to generate the spectral feature in rubidium vapour. The laser sources 3, 99 pass beams through optical isolators 91a-b, because being diode lasers they are sensitive to potential optical feedback coming back from the rest of the experiment. The beam from the control laser source 3 is split into two main beams: the probe beam 83b which is reflected off the subject 5 (a PZT mirror); and the coupling beam 83a required for EIA. The two beams 83a-b are overlapped and directed through rubidium cell 7b placed in a zero gauss chamber 98. A second repump laser source 99 is used to repopulate the $5^2S_{1/2}$ ground state. The frequencies of the lasers are monitored using a wavemeter 93a-b (Bristol Instruments). The beam splitters 94 used here are polarising beam splitters.

Control arm

The control laser 3 is formed using an ECDL configuration with a diode (EagleYard) tuned to 794.9 nm (377105.039 GHz), corresponding to the $5^2S_{1/2} \rightarrow 5^2P_{1/2}$ transition. The laser output is then split into two, the probe beam 93b and coupling beam 93a. The intensity of the beams 93a-b is controlled using half-wave plates 95 and are at 2.69 mW and 77 μW for the coupling and probe beams 93a-b respectively. Both beams 93a-b are directed through individual acousto-optic modulators (AOMs)

97a-b and retro-reflected to achieve frequency shifting without much displacement of the beams 93a-b. We use the first-order diffraction spot and block the zero-order using an aperture. The AOMs 97a-b and hence the beam frequencies are controlled using a digital waveform generator (j850 Australian National University). In our experiments, we keep the coupling beam frequency 93a fixed and vary the frequency of the probe beam 93b across 15 MHz to scan across the dispersive feature.

The probe beam 93b is reflected off either a mirror with a piezo attached to its back, or is directed through an electro-optic modulator (EOM) which generates the ultrasonic modulation. The probe and coupling beams are then recombined at a polarising beam splitter 94, with polarisation orthogonal to each other. The beams are then steered through a quarter wave plate 96 to convert to circular polarisation, then through the rubidium vapour cell 7b before detection using a photodetector 2c (low light).

The vapour cell 7b used is a vacuum sealed rubidium cell (Thorlabs CP25075-RB). To avoid splitting of the energy states due to Zeeman shifts, the cell 7b is placed in a three layered zero gauss chamber 98 (Magnetic Shields Corp). The cell 7b is heated at 90°C to increase optical depth using a water jacket.

Detection

After detection, the converted photocurrent was AC filtered and amplified (ZFL-500LN), then downconverted by mixing with the same signal used to generate the ultrasound. This postprocessed signal was then low pass filtered with cutoff frequency of 3 kHz, and amplified with 5× gain using an SRS preamplifier. The data was collected using an oscilloscope (Tektronix).

The method and apparatus used for detecting the ultrasound frequency is similar as the method and apparatus used for the first embodiment.

Repump arm

The repump laser 99 is also formed using an ECDL configuration with a 780 nm diode (Thorlabs). This laser is tuned to the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transition (384231.6 GHz) and has a power of 5.67 mW. The primary purpose of this laser 99 is to repopulate the $5^2S_{1/2}$ ground state which becomes depleted oyer time due to dephasing effects. The repump beam polarisation is adjusted to be the same as that of the coupling and is steered through at an angle entering the cell. This beam is blocked off using an aperture.

Results

Figure 18 shows the results showing ultrasound detection using the experimental setup described above. Subfigures Ml-4 show the retrieved signal generated with piezo-backed mirror after post processing for phase shifts of 0°-270°, in 90° increments. Subfigures El-4 show the retrieved signal generated with an EOM for the same phase shift. The frequency of the probe beam is scanned over 15 MHz to obtain this data. The signal generated by the EOM 92 can be used as a reference for the data retrieved using the mirror. The measured EIA feature is shown in Figure 18. From the data we measure an absorption of 0.4, which corresponds to a calculated maximum phase shift of 0.2 rad or 11°. This is currently not ideal as we require a phase shift of 90° to achieve total conversion between phase and amplitude modulation. The current absorption becomes saturated and is limited by the choice of vapour cell used. We can increase absorption by using a rubidium vapour cell with He buffer gas.

Figure 19 shows the measured EIA profile 1901, the fit to a model in 1902, and the phase shift calculated via the Kramers-Kronig relations in 1903. The calculated phase shift 1903 shows a maximum value of 0.2 rad.

We have demonstrated detection of ultrasound using EIA as a spectral feature in a rubidium vapour. The results can be optimised by using a different vapour cell.

In at least a preferred version of the second embodiment, both the probe and coupling beams are detuned away from the doppler broadened transition. In this situation the phase-to-amplitude modulation conversion can be best understood resulting from the dispersion seen by light around the probe frequency. Only a linear response of the probe beam is required in a system of the second embodiment. In principle, optimal sensitivities can be achieved, by phase shifting the carrier 90 degrees and leaving the sidebands unaffected. In at least a preferred embodiment, the phase-to-amplitude modulation conversion works with arbitrarily low probe powers. Additionally, the Raman absorption features in a system of the second embodiment can be much narrower than 1 MHz, meaning that a preferred embodiment system can be used to detect ultrasound with low frequencies.

In both the first and second embodiments, the dominant carrier component is phase shifted by 90°. It is preferred that the major sidebands have no or minimal attenuation. However, some attenuation of the major sidebands is allowable provided that sufficient energy of the major sidebands can pass through the resonant medium to enable ultrasound to be detected with sufficient accuracy. The signal may have additional lower order sidebands, however in most situations these will be small because the ultrasonic displacement that are being measured are small compared to the wavelength of light. As a result, these lower order sidebands have practically no effect on the amplitude modulation of the signal. Accordingly, the system may be configured such that generally, those additional side bands will be absorbed by the resonant medium, due to their low intensity. However, those additional side bands could pass through the resonant medium with litde or no attenuation.

Embodiments of the invention have been described by way of example only and modifications may be made thereto without departing from the scope of the invention.

For example, it will be appreciated that the apparatus and method features can modified while still enabling the invention to function. Additionally, other resonant media could be used. For example, for the second preferred embodiment, other alkali metals, including but not limited to Li, Na, K, Rb, Cs, iodine, ammonia, or acetylene could be used as the gas or vapour, as they have strong transitions with wavelengths suitable for lasers.

As another example, in the embodiments described above, reference has been made to a beam reflecting off a vibrating subject and being passed through a resonant medium. Rather than reflecting off the vibrating subject, the beam may alternatively be passed or transmitted through the vibrating subject and then passed through the resonant medium.

Further, the beam is described above as being a phase modulated beam. Alternatively, the beam could be a frequency modulated beam. Within the limit of small modulation, such as that being referred to herein for ultrasound detection, a phase modulated beam and a frequency modulated beam are the same.

Claims:

1. A method of detecting ultrasound vibrations of a subject, the method comprising:

passing a modulated beam from a vibrating subject through a resonant medium wherein the modulated beam has a carrier frequency component and two major sideband frequency components, wherein the resonant medium imparts a phase shift on the carrier frequency component and passes the two major sideband frequency components to output an amplitude modulated signal; and

detecting the ultrasound vibrations of the subject from the amplitude modulated signal.

2. The method of claim 1, wherein the resonant medium passes the two major sideband frequency components of the beam with miriimal or zero attenuation.

3. The method of claim 1, further comprising the step of transmitting a beam to the vibrating subject, wherein at least part of the transmitted beam interacts with the vibrating subject.

4. The method of claim 3, wherein the transmitted beam has a wavelength substantially the same as, or close to, a resonance in the resonant medium.

5. The method of claim 3 or 4, wherein the transmitted beam has a wavelength close to a narrow peak in the resonant medium's absorption spectrum.

6. The method of claim 5, wherein the peak is less than about 2 nm wide.

7. The method of claim 5 or 6, wherein the wavelength of the transmitted beam is closer to a centre of the peak than about forty times the full-width half-maximum width of the peak.

8. The method of any one of claims 3 to 7, wherein the transmitted beam is a laser beam.

9. The method of any one of the preceding claims, wherein the resonant medium imparts a phase shift of substantially 90° on the carrier frequency component of the modulated beam.

10. The method of any one of the preceding claims, wherein the amplitude modulated signal comprises a carrier signal component with an amplitude that is modulated by a modulation signal having a modulation frequency, wherein the modulation frequency is proportional to a frequency of the vibrations of the subject.

11. The method of claim 10, wherein the modulation frequency is proportional to the difference between the carrier frequency of the modulated beam and one of the two major sideband frequency components.

12. The method of claim 10 or 11, wherein the step of detecting the ultrasound vibrations comprises the step of detecting the modulation signal.

13. The method of claim 12, wherein the modulation signal is detected using a digital signal processor.

14. The method of any one of the preceding claims, wherein the resonant medium comprises a rare-earth ion doped crystal, and the method comprises spectrally burning a hole in the crystal.

15. The method of claim 14, wherein the hole is slightly offset from the carrier frequency component of the modulated beam to impart the phase shift on the carrier frequency component of the modulated beam.

16. The method of claim 14, wherein the resonant medium comprises a rare-earth ion doped crystal, in which more than one hole has been spectrally burned.

17. The method of any one of claims 14 to 16, wherein the rare-earth ion doped crystal comprises ion(s) that is/are selected from the group comprising Praseodymium (Pr), Neodymium (Nd), Europium (Eu), Erbium (Er), Thulium (Tm), Ytterbium (Yb).

18. The method of any one of claims 14 to 17, wherein the rare-earth ion doped crystal comprises a crystal that is selected from the group comprising lanthanum fluoride (LaF_3), Yttrium orthosiHate (Y_2Si0_5), Yttrium (III) Vanadate ($YV0_4$), Yttrium-Aluminium-Garnet (YAG).

19. The method of claim 18, wherein the resonant medium comprises Tm^{3+} ions doped in a YAG crystal.

20. The method of any one of claims 14 to 19, wherein the spectral hole(s) is/are burnt into the rare-earth crystal before the modulated beam is passed through the crystal.

21. The method of any one of claims 14 to 19, wherein the spectral hole(s) is/are burnt into the rare-earth crystal concurrendy with the modulated beam being passed through the crystal.

22. The method of any one of claims 14 to 21, further comprising holding the resonant medium is at a cryogenic temperature.

23. The method of any one of claims 14 to 22, further comprising the steps of:

transmitting a laser beam from a laser source to the vibrating subject, wherein at least part of the laser beam interacts with the subject; and

performing frequency stabilisation on the laser beam.

24. The method of claim 23, wherein the step of performing frequency stabilisation comprises using a combination of optical and electronic feedback to the laser source.

25. The method of claim 24, wherein the step of performing frequency stabilisation comprises using part of the laser beam that has passed through the resonant medium for optical feedback and part of the laser beam that has passed through the resonant medium for electronic feedback.

26. The method of claim 25, wherein the step of performing frequency stabilisation comprises the step of delivering a part of the laser beam that has passed through the resonant medium to a detector, to determine the frequency difference between the laser beam and a spectral hole in the resonant medium and from the frequency difference, adjusting the laser beam frequency substantially to the centre of the spectral hole.

27. The method of claim 26, wherein the step of performing frequency stabilisation comprises delivering a part of the laser beam that has passed through the resonant medium back into the laser source to provide optical feedback to the laser source.

28. The method of any one of claims 1 to 13, wherein the resonant medium comprises a gas or vapour which is adapted to function as a-sharp frequency discriminator.

29. The method of claim 28, wherein the resonant medium comprises a molecular gas or an atomic vapour.

30. The method of claim 29, wherein the gas or vapour comprises an alkali metal vapour.

31. The method of claim 30, wherein the gas or vapour is selected from the group comprising lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb), iodine, ammonia, acetylene, Cesium (Cs).

32. The method of any one of claims 28 to 31, further comprising passing a signal from a coupling beam and the modulated beam, into the gas or vapour.

33. The method of claim 32, wherein the coupling beam and the modulated beam are detuned away from a doppler broadened transition of the gas or vapour, to make use of offresonant Raman transitions.

34. The method of claim 32 or 33, comprising passing the coupling beam and the modulated beam through a polarising beam splitter and directing the signal that is output from the beam splitter into the gas or vapour.

35. The method of any one of claims 32 to 34, further comprising the step of transmitting a beam to the vibrating subject, wherein at least part of the beam interacts with the subject; and wherein the coupling beam is obtained from the transmitted beam.

36. The method of claim 35, wherein, in the case of atomic vapour or molecular gas, the transmitted beam has a wavelength close to, or substantially the same as a resonance in the resonant medium.

37. The method of any one of claims 28 to 36, wherein the gas or vapour is at a temperature of between about 20°C and about 25°C.

38. The method of any one of claims 28 to 36, wherein, when an atomic vapour is used, the vapour is at a temperature of between about 20°C and about 150°C.

39. The method of any one of claims 1 to 38, wherein the modulated beam is a phase modulated beam.

40. An apparatus for detecting ultrasound vibrations of a subject, wherein the apparatus is adapted to receive a modulated beam from the subject, the modulated beam having two major sideband components and a carrier frequency component, the apparatus comprising:

a resonant medium adapted to pass the major sideband frequency components and to pass the carrier frequency component and impart a phase shift on the carrier frequency component to convert the modulated beam to an amplitude modulated signal;

the apparatus configured to detect the ultrasound vibrations from the amplitude modulated signal.

41. The method of claim 40, wherein the resonant medium passes the two major sideband frequency components of the beam with minimal or zero attenuation.

42. The apparatus of claim 40 or 41, further comprising a transmitter for transmitting a beam to the vibrating subject, wherein at least part of the beam interacts with the vibrating subject.

43. The apparatus of claim 42, wherein the transmitted beam has a wavelength substantially the same as, or close to, a resonance in the resonant medium.

44. The apparatus of claim 42 or 43, wherein the transmitted beam has a wavelength close to a narrow peak in the resonant medium's absorption spectrum.

45. The apparatus of claim 44, wherein the peak is less than about 2 nm wide.

46. The apparatus of any one of claims 43 to 45, wherein the wavelength of the transmitted beam is closer to a centre of the peak than forty times the full-width half-maximum width of the peak.

47. The apparatus of any one of claims 42 to 46, wherein the transmitted beam is a laser beam.

48. The apparatus of any one of claims 40 to 47, wherein the resonant medium imparts a phase shift of substantially 90° on the carrier frequency component of the modulated beam.

49. The apparatus of any one of claims 40 to 48, wherein the amplitude modulated signal comprises a modulation signal having a modulation frequency, wherein the modulation frequency is proportional to the vibrations of the subject.

50. The apparatus of any one of claims 40 to 49, further comprising a detector for detecting the ultrasound vibrations, wherein the detector is adapted to detect the ultrasound vibrations from the modulation signal.

51. The apparatus of claim 50, wherein the detector comprises a digital signal processor.

52. The apparatus of any one of claims 40 to 51, wherein the apparatus is adapted for remote detection of ultrasound, wherein no part of the apparatus, other than the beam, physically contacts the subject.

53. The apparatus of any one of claims 40 to 52, wherein the resonant medium comprises a rare-earth ion doped crystal, in which a hole has been spectrally burned into the crystal.

54. The apparatus of claim 53, wherein the hole is slightly offset from the carrier frequency component of the modulated beam to impart the phase shift on the carrier frequency component of the modulated beam.

55. The apparatus of claim 53 or 54, the resonant medium comprises a rare-earth ion doped crystal in which more than one hole has been spectrally hole burned into the crystal.

56. The apparatus of any one of claims 53 to 55, wherein the rare-earth ion doped crystal comprises ion(s) that is/ are selected from the group comprising Praseodymium (Pr), Neodymium (Nd), Europium (Eu), Erbium (Er), Thulium (Tm), Ytterbium (Yb).

57. The apparatus of any one of claims 53 to 56, wherein the rare-earth ion-doped crystal comprises a crystal that is selected from the group comprising lanthanum fluoride (LaF_3), Yttrium orthosiliate (Y_2Si0_5), Yttrium (III) Vanadate ($YV0_4$), Yttrium-Aluminium-Garnet (YAG).

58. The apparatus of any one of claims 53 to 57, wherein the apparatus is configured to burn the spectral hole(s) into the rare-earth crystal before the modulated beam is passed through the crystal.

59. The apparatus of any one of claims 53 to 57, wherein the apparatus is configured to burn the spectral hole(s) into the rare-earth crystal concurrently with the modulated beam being passed through the crystal.

60. The apparatus of any one of claims 53 to 59, wherein the apparatus comprises a cryostat to hold the resonant medium at a cryogenic temperature.

61. The apparatus of any one of claims 53 to 60, further comprising a frequency stabilisation system to perform frequency stabilisation on a laser beam that is transmitted to the vibrating subject from a laser source.

62. The apparatus of claim 61, wherein the frequency stabilisation system provides a combination of optical and electronic feedback to the laser source.

63. The apparatus of claim 61 or 62, wherein the frequency stabilisation system is configured to use part of the beam that has passed through the resonant medium for optical feedback and part of the beam that has passed through the resonant medium for electronic feedback.

64. The apparatus of any one of claims 61 to 63, wherein the frequency stabilisation system is configured to deliver a part of the beam that has passed through the resonant medium to a detector, to determine the frequency difference between the laser beam and a spectral hole in the resonant medium and from the frequency difference, to adjust the laser beam frequency substantially to the centre of the spectral hole.

65. The apparatus of any one of claims 61 to 64, wherein the frequency stabilisation system is configured to deliver a part of the beam that has passed through the resonant medium back into the laser source to provide optical feedback to the laser source.

66. The apparams of claim 40 to 52, wherein the resonant medium comprises a gas or vapour which is adapted to function as a sharp frequency discriminator.

67. The apparatus of claim 66, further comprising a gas cell which contains the gas or vapour.

68. The apparatus of claim 66 or 67, wherein the resonant medium comprises a molecular gas or an atomic vapour.

69. The apparams of claim 68, wherein the gas or vapour comprises an alkali metal vapour.

70. The apparams of claim 69, wherein the gas or vapour is selected from the group comprising lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb) , iodine, ammonia, acetylene, Cesium (Cs).

71. The apparams of any one of claims 66 to 70, wherein the apparatus is configured to pass a signal from a coupling beam and the modulated beam, into the gas or vapour.

72. The method of claim 71, wherein the coupling beam and the modulated beam are detuned away from a doppler broadened transition of the gas or vapour, to make use of offresonant Raman transitions.

73. The method of claim 71 or 72, wherein the apparatus is configured to pass the coupling beam and the modulated beam tlirough a polarising beam splitter and to direct the signal that is output from the beam splitter into the gas or vapour.

74. The apparatus of any one of claims 71 to 73, wherein the apparatus is adapted to generate the coupling beam from the transmitter.

75. The apparatus of any one of claims 66 to 74, wherein the gas or vapour is at a temperature of between about 20°C and about 25°C.

76. The apparatus of any one of claims 66 to 74, wherein, when an atomic vapour is used, the vapour is at a temperature of between about 20°C and about 150°C.

77. The apparatus of any one of claims 40 to 76, wherein the modulated beam is a phase modulated beam.

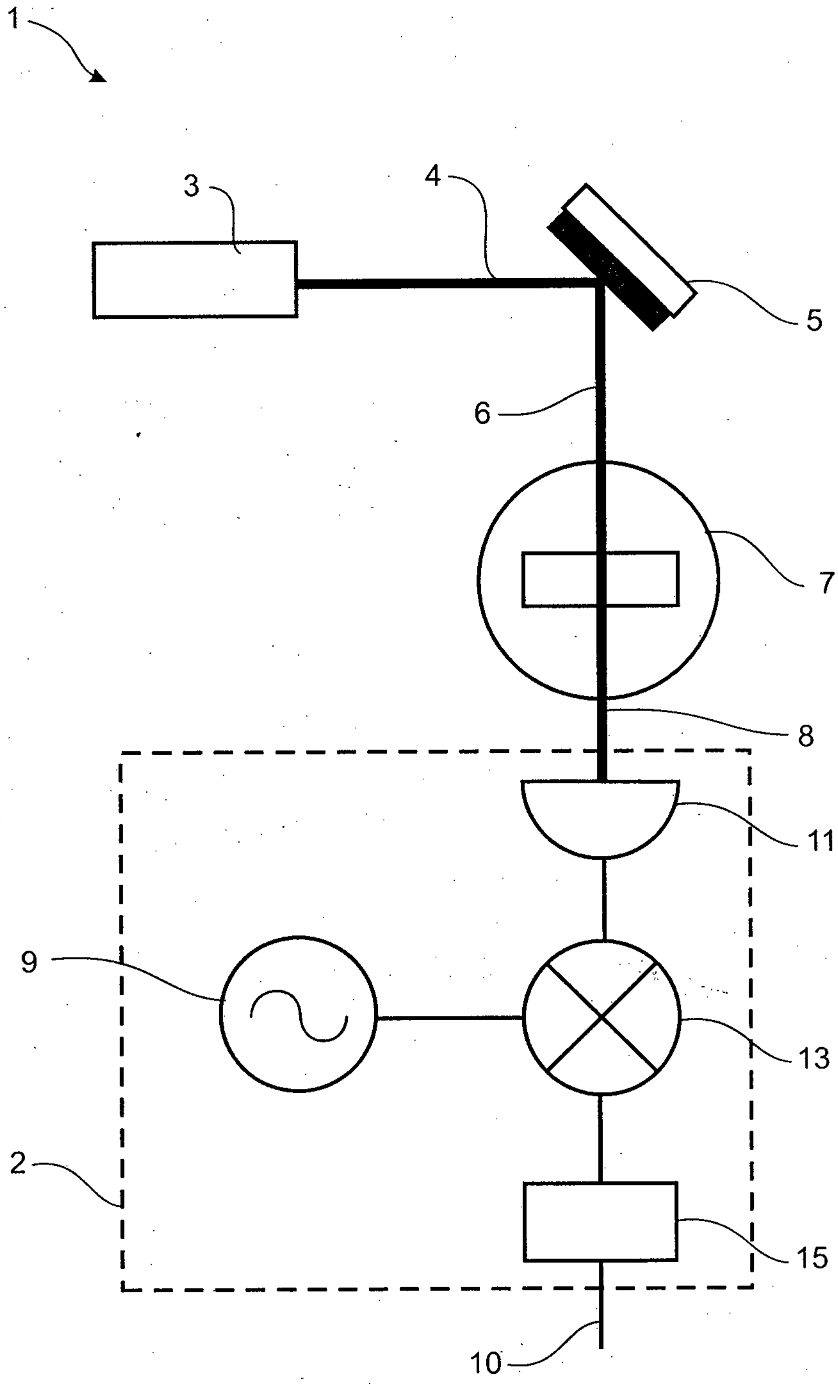


FIGURE 1

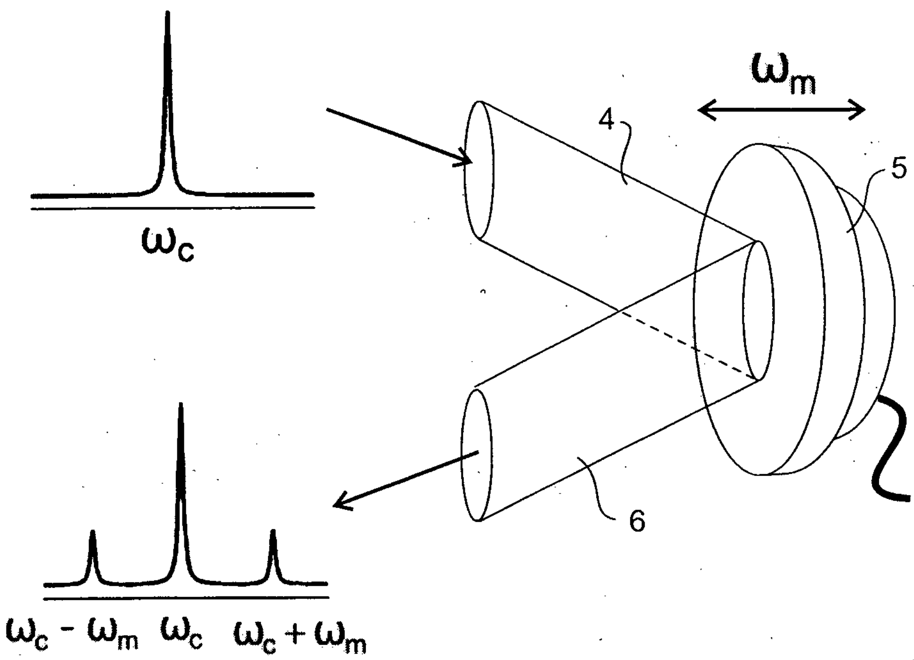


FIGURE 2

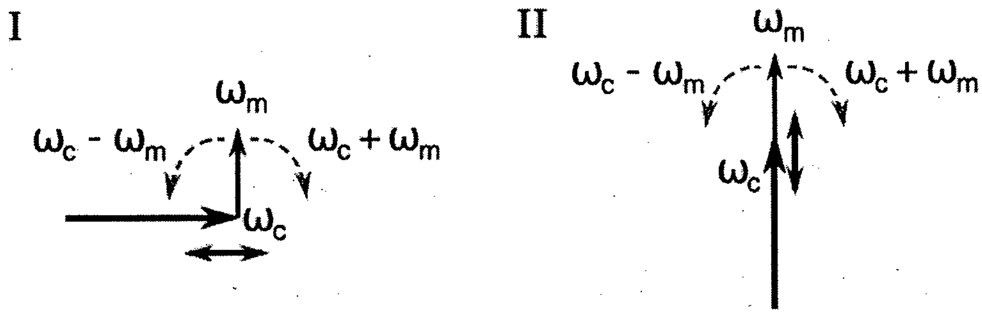
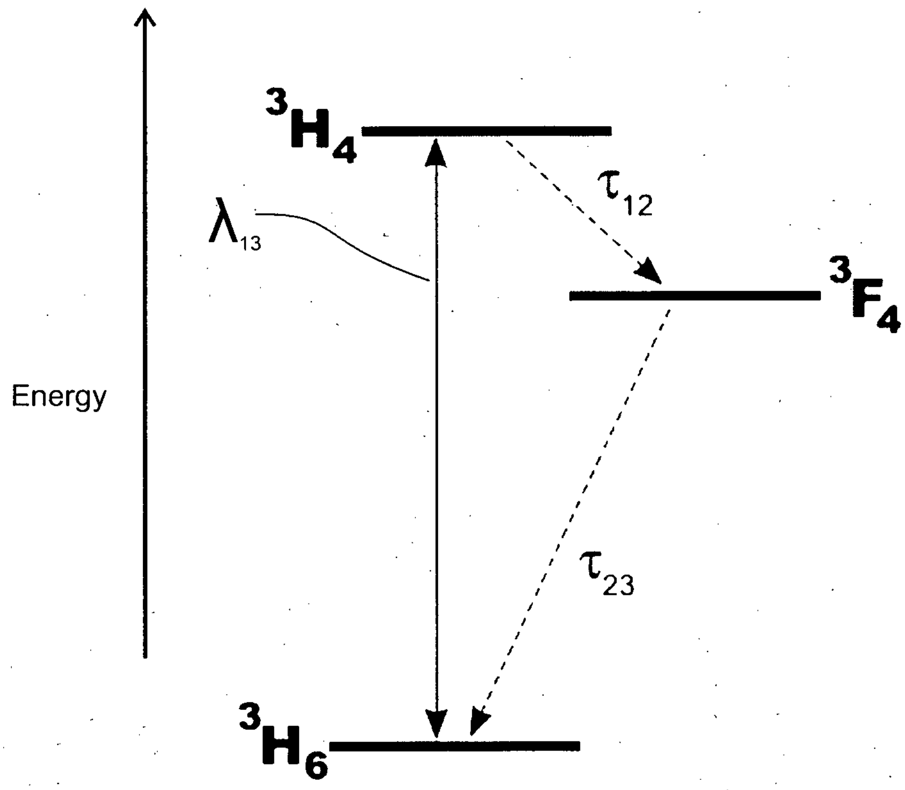


FIGURE 3



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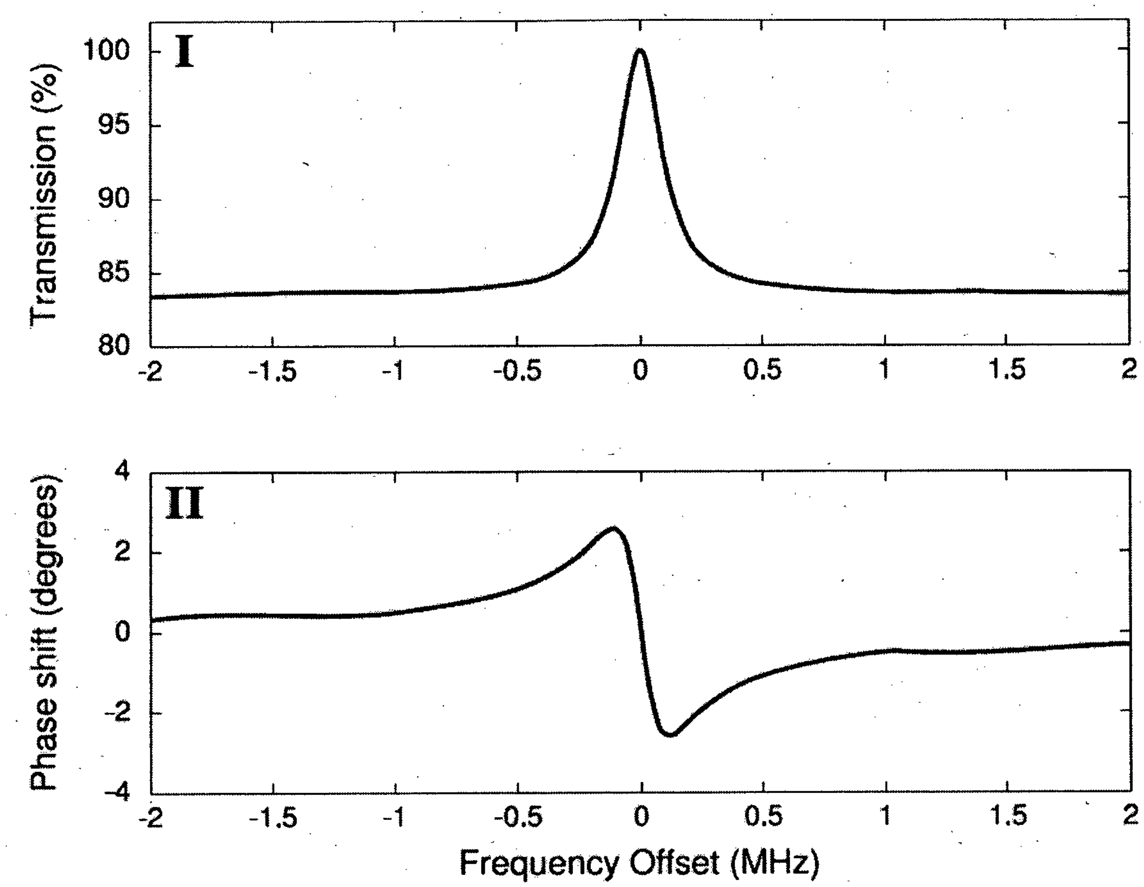

FIGURE 5

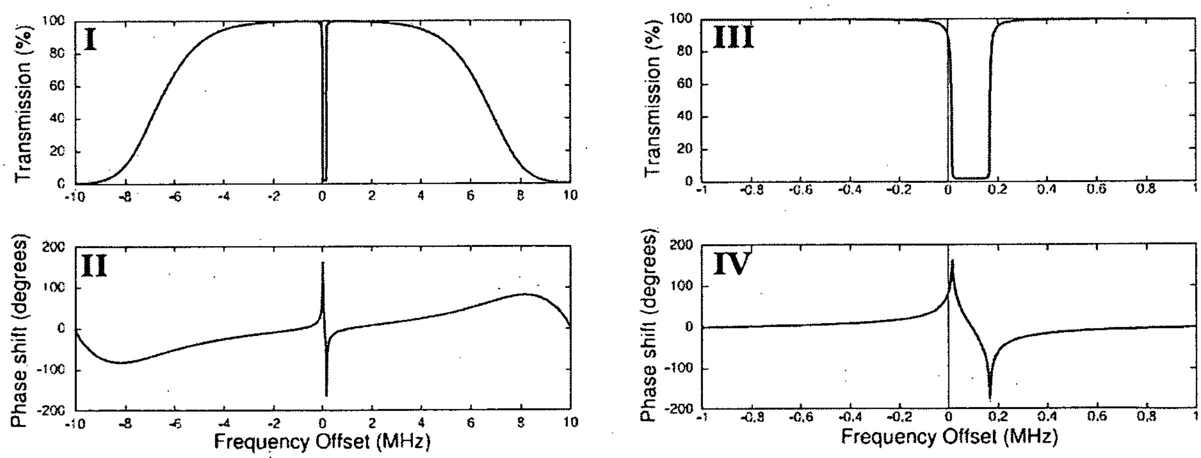

FIGURE 6

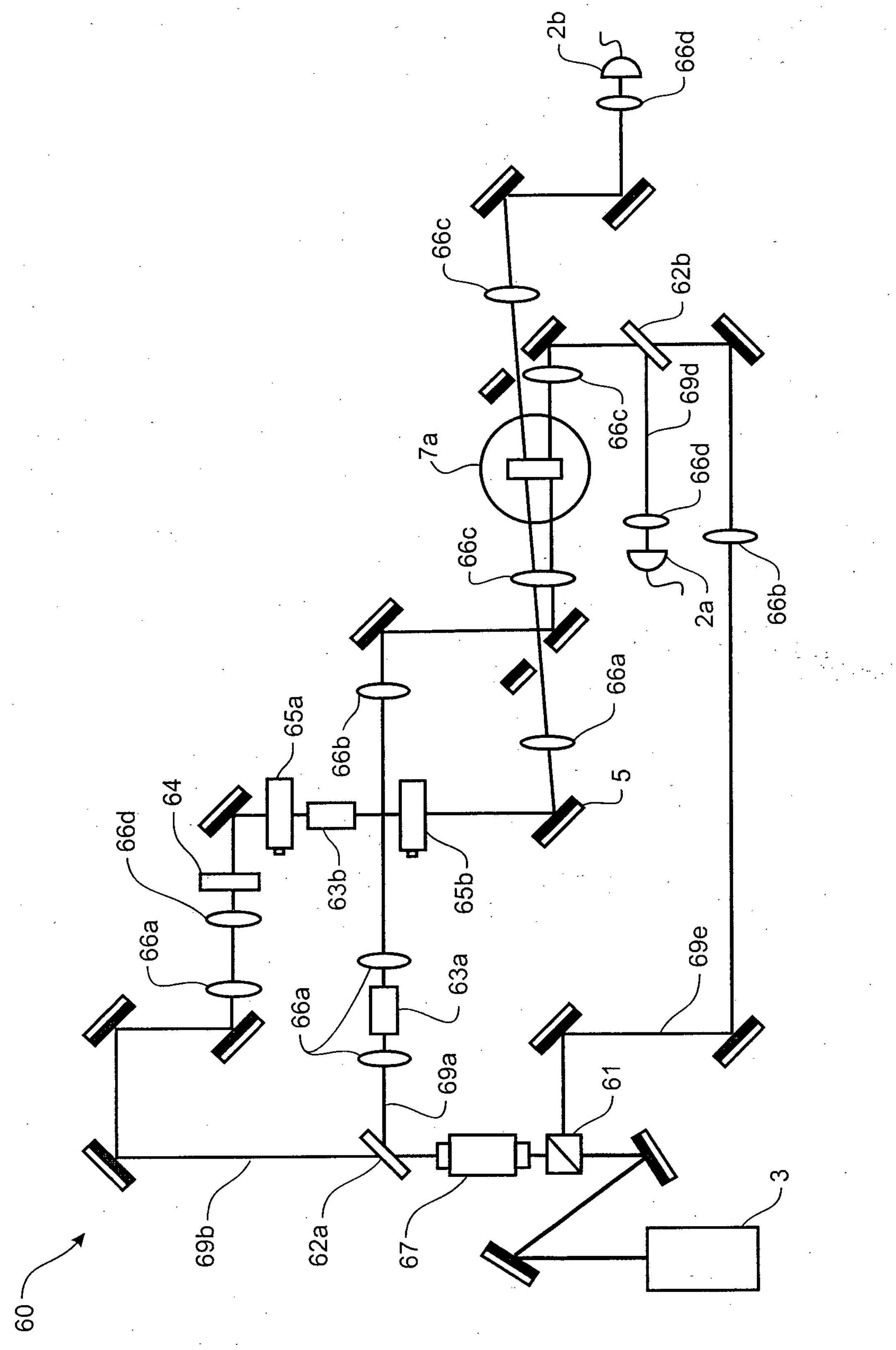
60
69b
62a
67
3
61
69a
66a
63a
66a
66d
64
65a
66b
63b
65b
5
66a
66c
7a
66c
66c
62b
69d
66d
2a
66b
69e
2b
66d

FIGURE 7

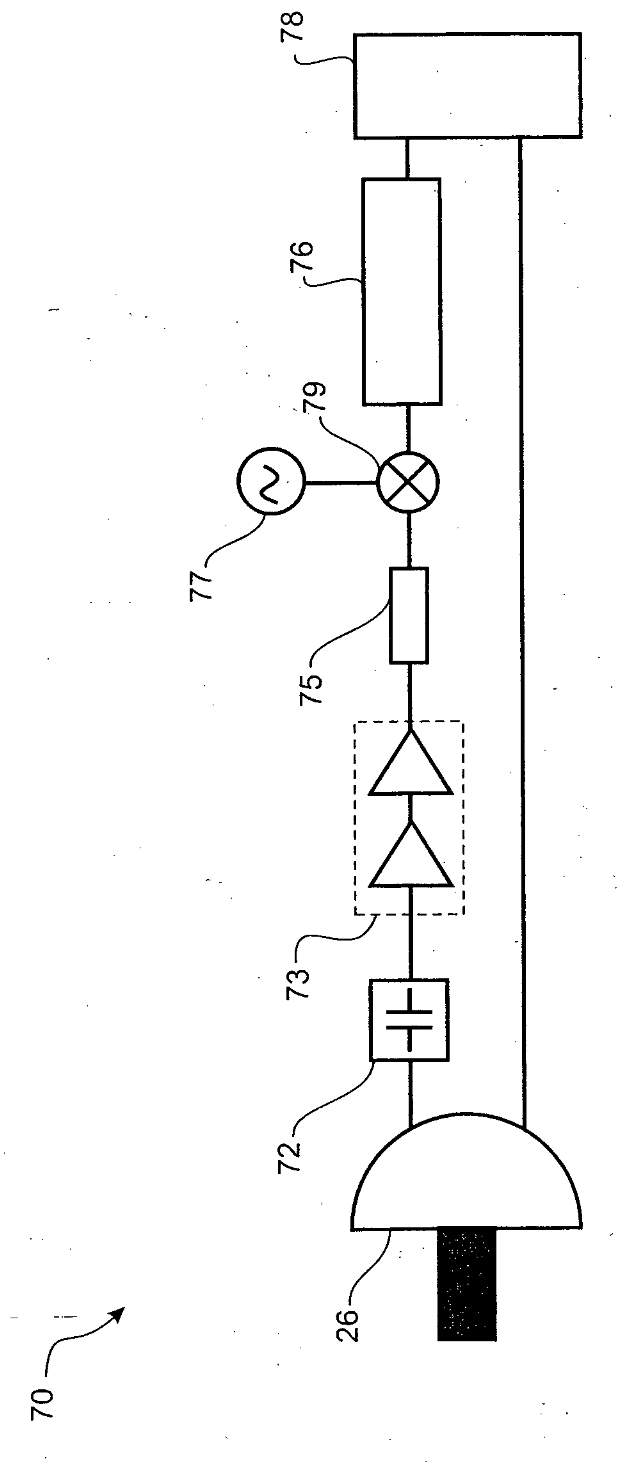

FIGURE 8

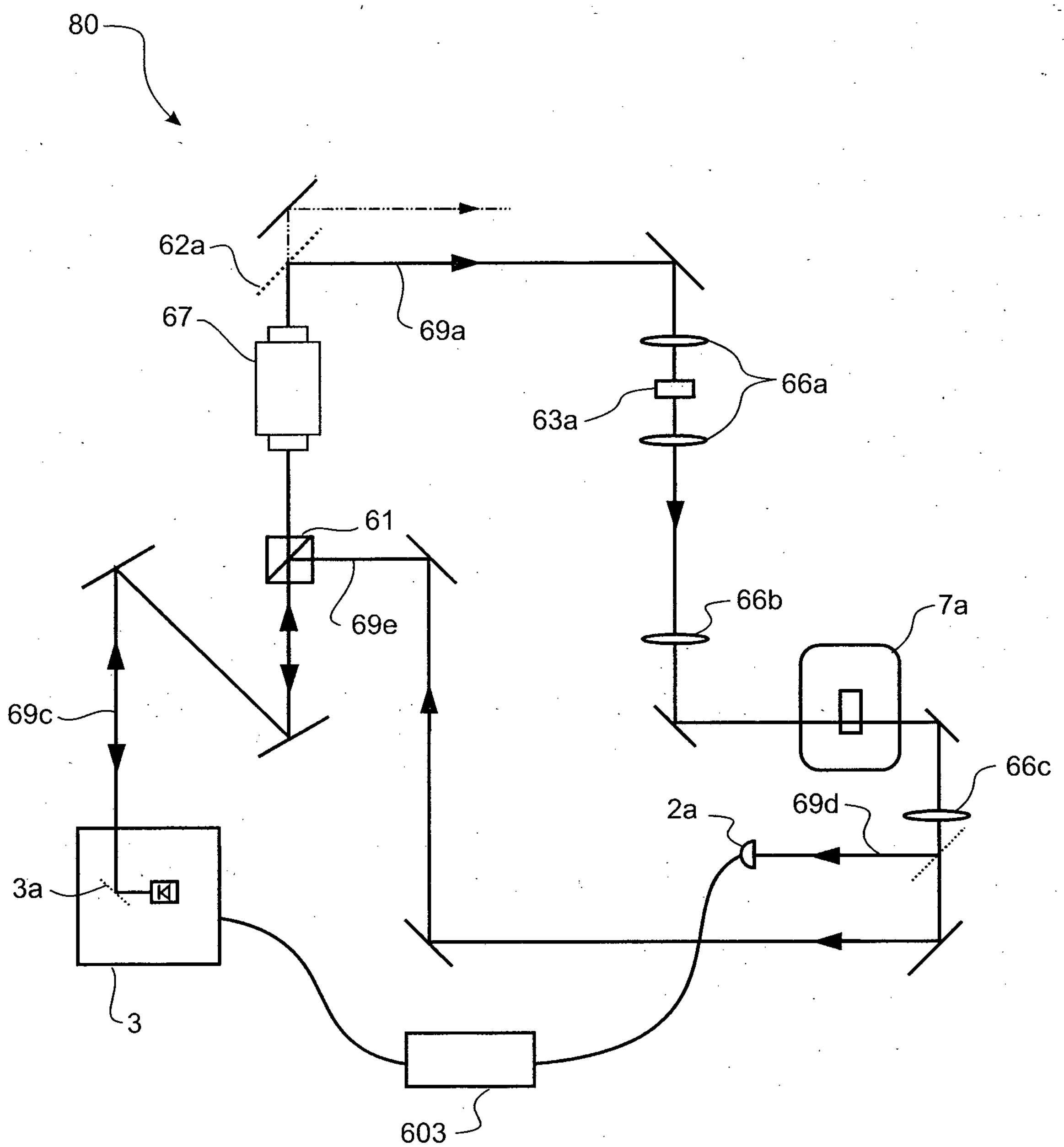

FIGURE 9

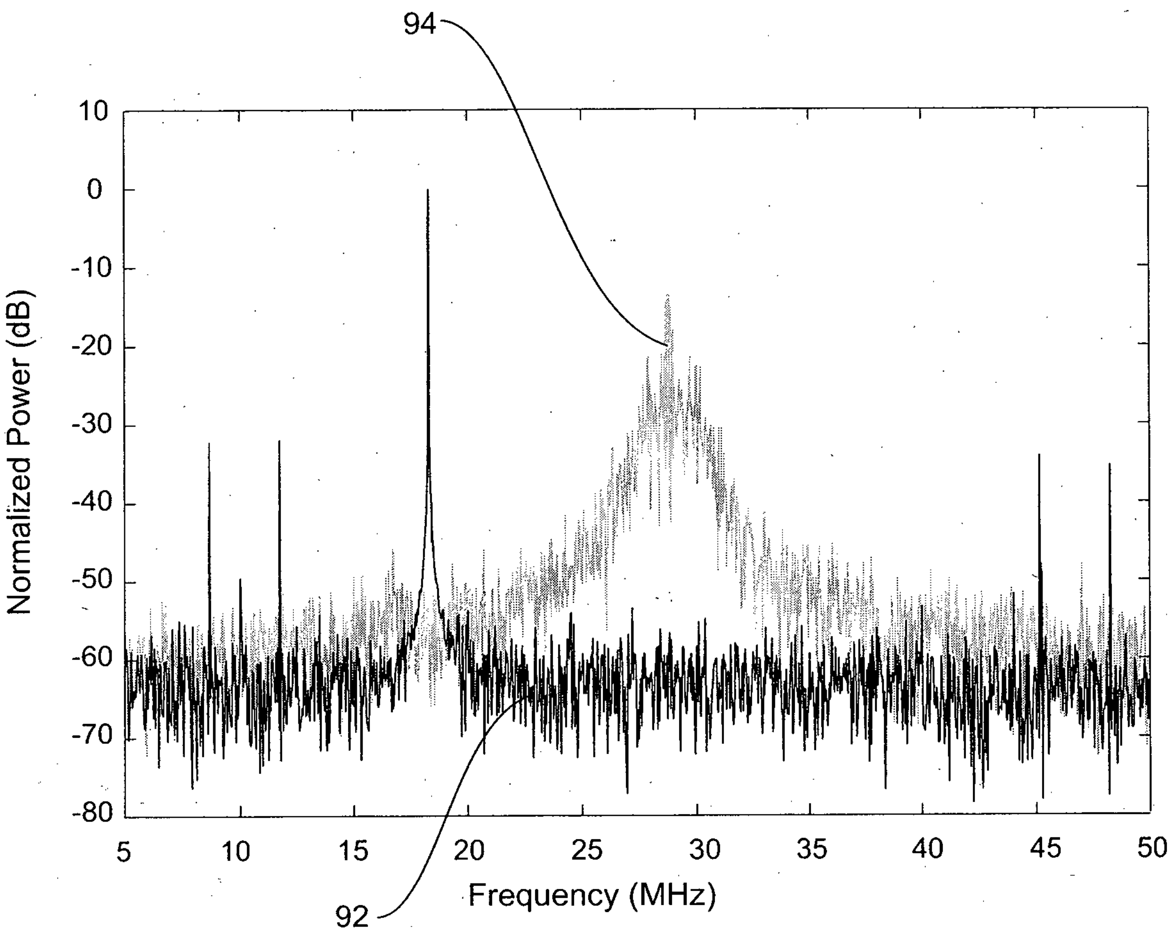
94
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Normalized Power (dB)
5
10
15
20
25
30
35
40
45
50
Frequency (MHz)
92

FIGURE 10

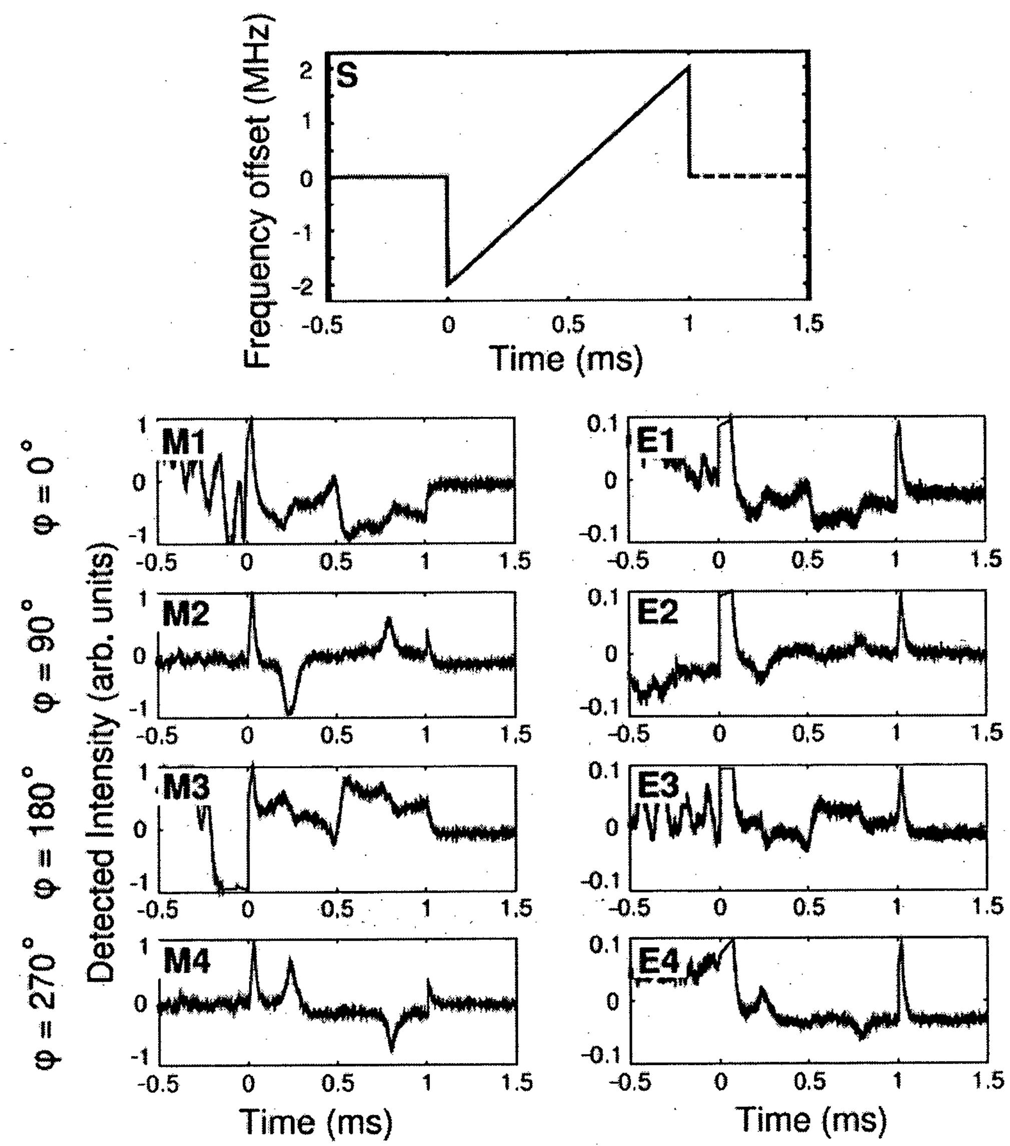
S
Frequency offset (MHz)
2
1
0
-1
-2
-0.5
0
0.5
1
1.5
Time (ms)
M1
M2
M3
M4
E1
E2
E3
E4
φ = 0°
φ = 90°
φ = 180°
φ = 270°
Detected Intensity (arb. units)
0.1
-0.1
Time (ms)
Time (ms)

FIGURE 11

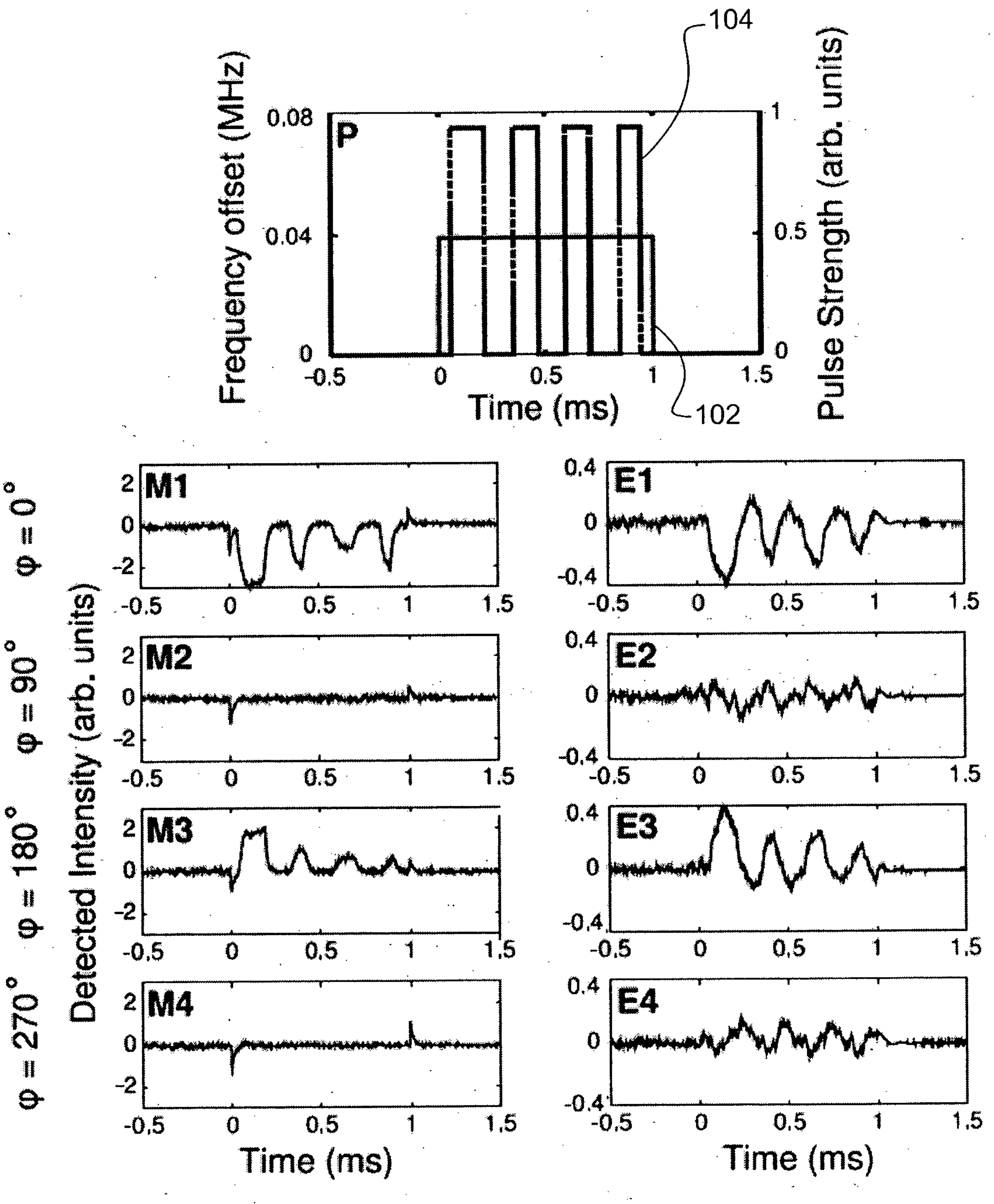
104
102
P
Frequency offset (MHz)
Pulse Strength (arb. units)
Time (ms)
M1
M2
M3
M4
E1
E2
E3
E4
φ = 0°
φ = 90°
φ = 180°
φ = 270°
Detected Intensity (arb. units)
Time (ms)
Time (ms)

FIGURE 12

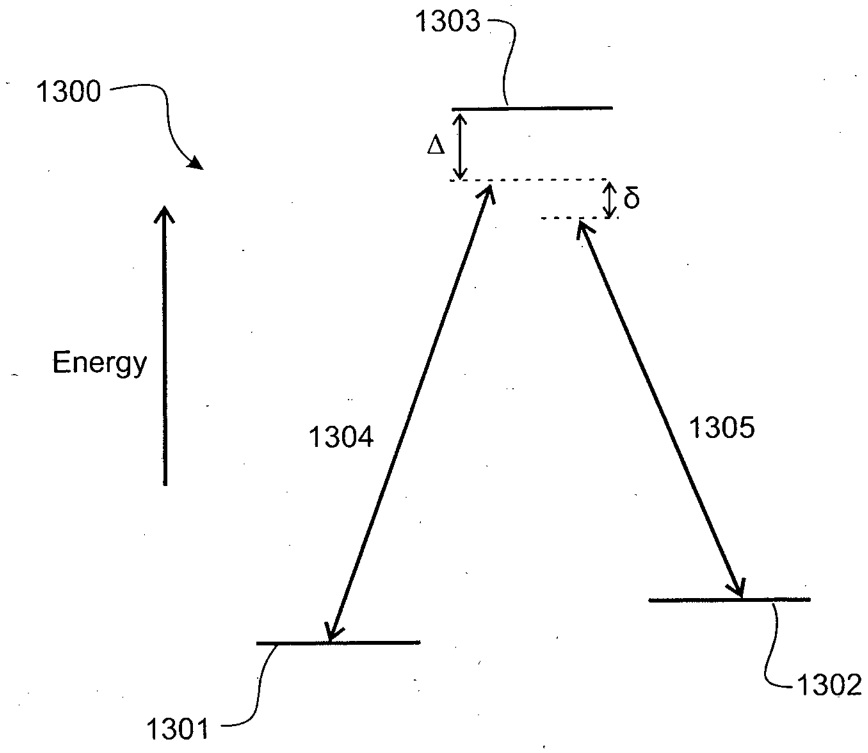

FIGURE 13

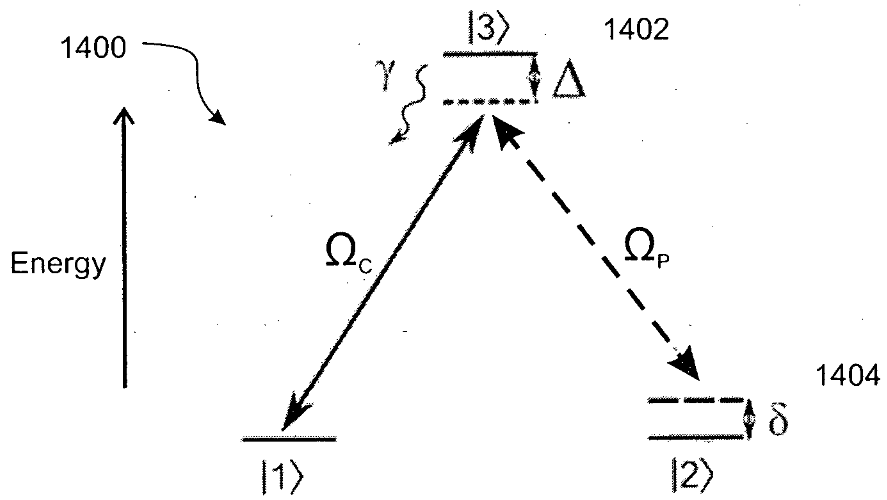

FIGURE 14

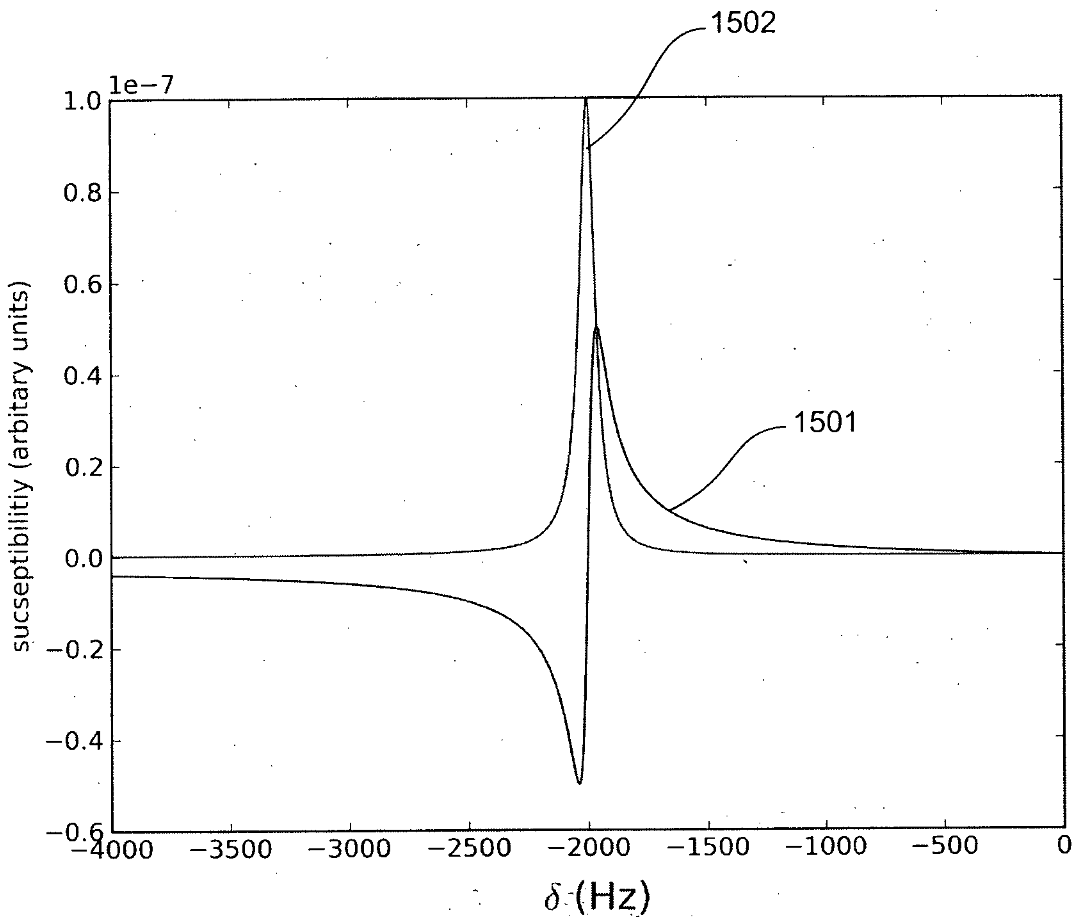
1502
1e−7
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
sucseptibilitiy (arbitary units)
1501
−4000
−3500
−3000
−2500
−2000
−1500
−1000
−500
0
δ (Hz)

FIGURE 15

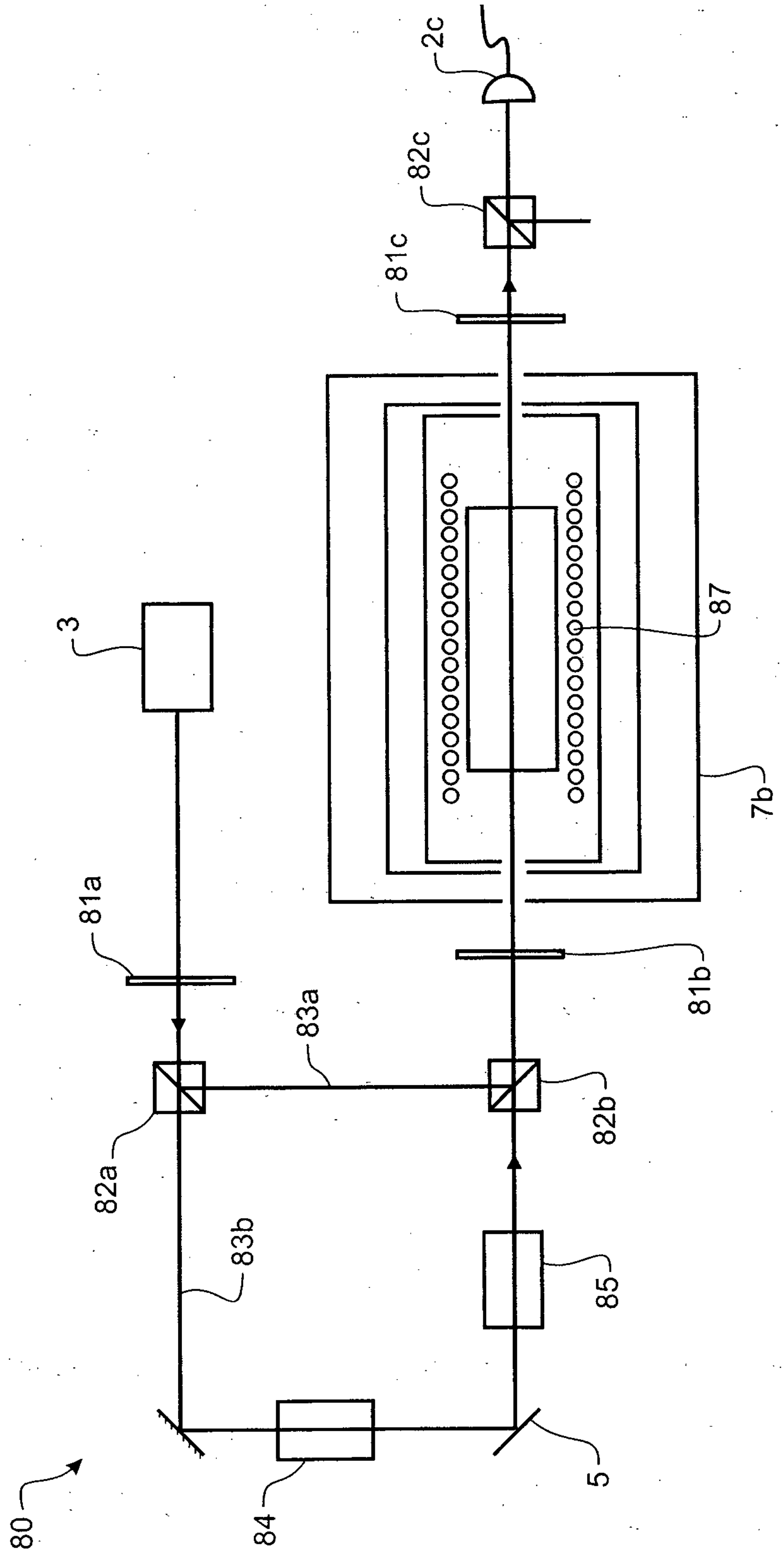

FIGURE 16

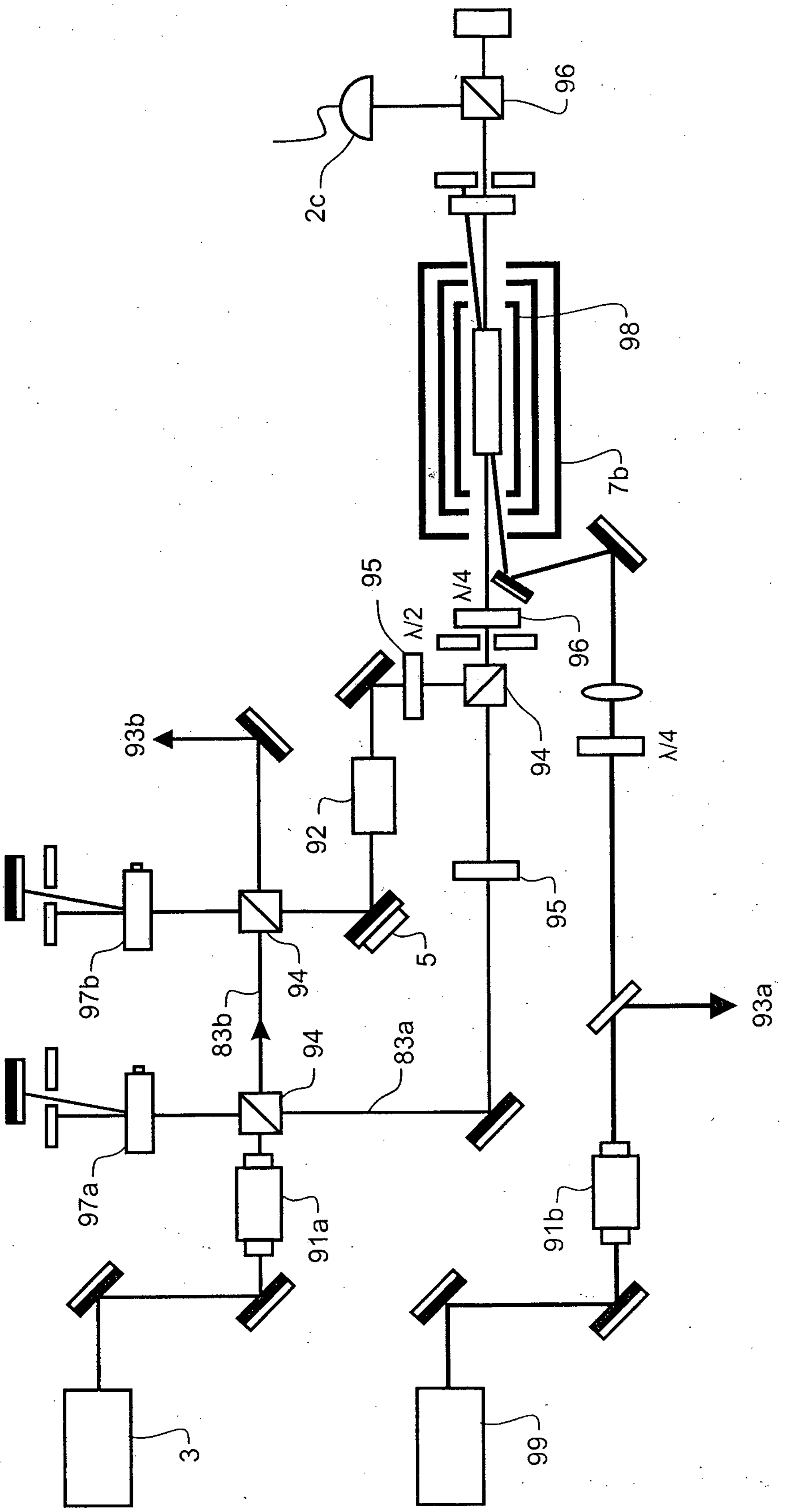
2c
96
98
7b
95
λ/2
λ/4
96
94
93b
92
95
λ/4
97b
94
5
93a
97a
83b
94
83a
91a
91b
3
99

FIGURE 17

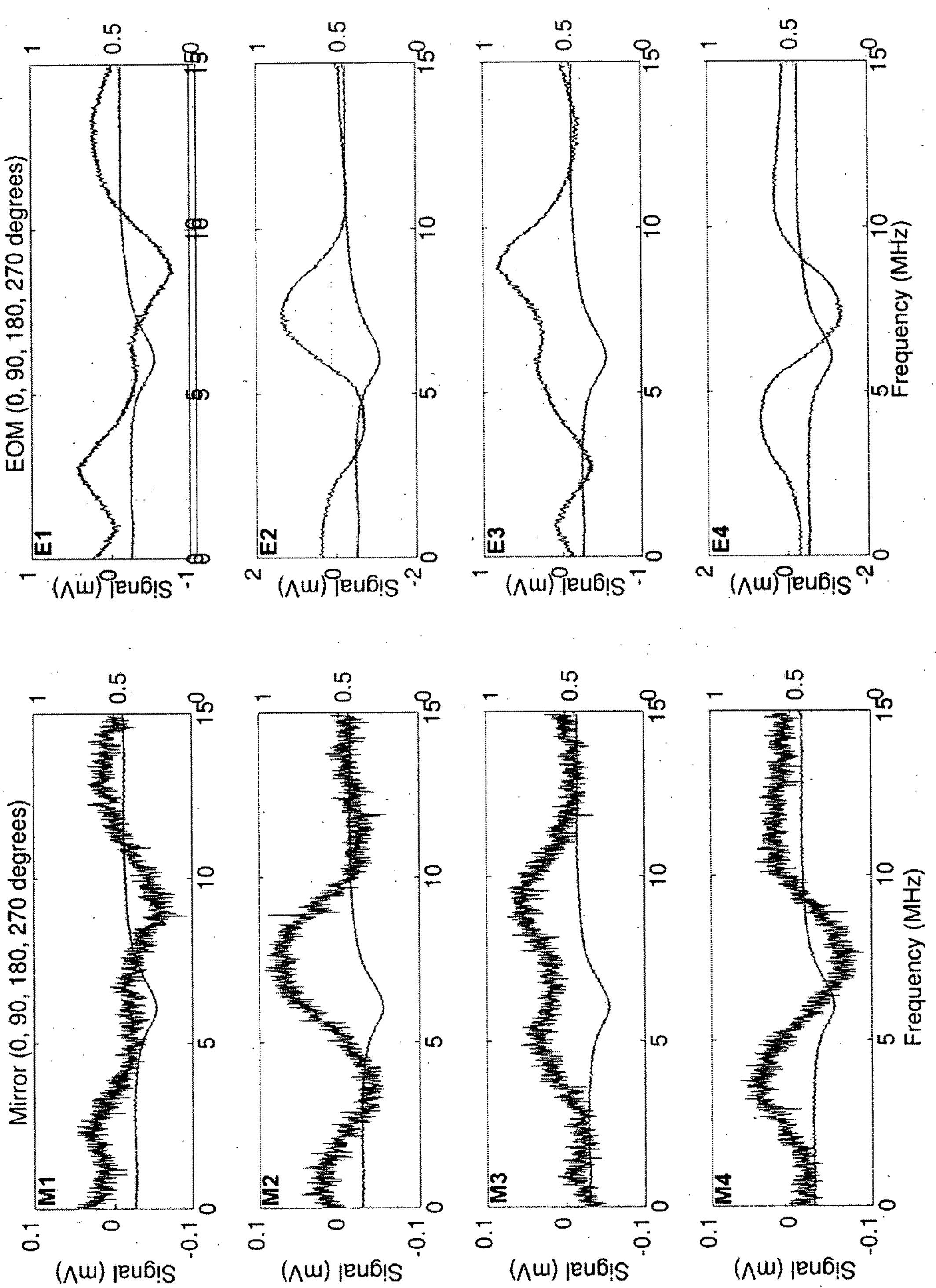
Mirror (0, 90, 180, 270 degrees)
EOM (0, 90, 180, 270 degrees)
M1
M2
M3
M4
E1
E2
E3
E4
Signal (mV)
Frequency (MHz)

FIGURE 18

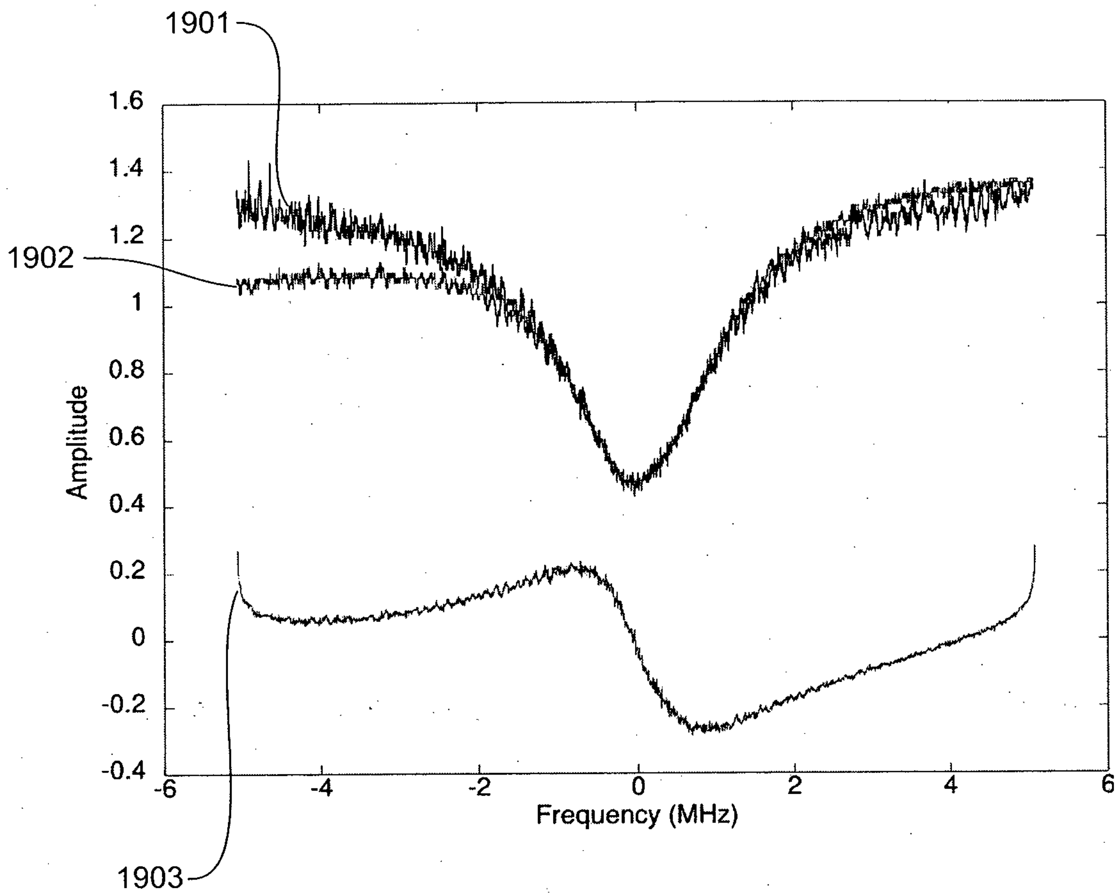
1901
1902
1903
Amplitude
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-6
-4
-2
0
2
4
6
Frequency (MHz)

FIGURE 19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NZ2010/000233

A. CLASSIFICATION OF SUBJECT MATTER

Int. CI.

G01N 29/56 (2006.01) *G01N 29/44* (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)
WPI, EPODOC and INSPEC using keywords: amplitude, phase, modulate, shift, ultrasound, ultrasonic, subband, sideband, carrier, resonant, resonance, vibrate, oscillate, medium, body, absorber and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4345475 A (BICKEL) 24 August 1982 See whole document	
A	US 2004/0066516 A1 (DEASON et al.) 8 April 2004 Abstract, Page 1	
A	WO 2005/069997 A2 (NORTHEASTERN UNIVERSITY et al.) 4 August 2005 Abstract, Figures 1-5	
A	WO 2008/011055 A1 (LOCKHEED MARTIN CORPORATION) 24 January 2008 Abstract	

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

* Special categories of cited documents:

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"E" earlier application or patent but published on or after the international filing date

"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)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
01 March 2011	-3 MAR 1011

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This Annex lists the known "A" publication level 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 Cited in Search Report		Patent Family Member					
US	4345475	DE	3002620				
US	20040665 16	AU	2003284030	US	6836336	WO	2004034079
WO	2005069997	US	2008094633	US	7652773		
WO	20080 11055	AU	20072757 19	CA	265 7790	ON	10 1529242
		EP	2047242	KR	200900403 18	US	20080 16965
		US	76 12894				

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 200 1.

END OF ANNEX