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PATENT APPLICATION

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NON-LINEAR OPTICAL CRYSTAL VIBRATION SENSING DEVICE
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901,289

NON-LINEAR OPTICAL CRYSTAL VIBRATION SENSING DEVICE

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9 NON-LINEAR OPTICAL CRYSTAL VIBRATION SENSING DEVICE

10
11 BACKGROUND OF THE INVENTION
12

13 The invention described herein arose in the course
14 of, or under, contract No. DE-AC03-89SF18433 between the
15 United States Department of Energy and Lawrence Livermore
16 National Laboratory.

17 The present invention relates generally to vibration
18 sensing apparatus, and more particularly to a means for
19 sensing vibration in a non-linear optical crystal using
20 laser beams.

21 A great variety of means and methods for sensing
22 vibration have been developed. An example is found in U.S.
23 Patent No. 4,471,659, issued to Udd et al.. Some of these
24 have taken advantage of the properties of crystals, such as
25 that disclosed in U.S. Patent No. 4,900,919, issued to
26 Twerdochlib. Other methods for detecting vibration have
27 utilized coherent light beams, such as the method described
28 in U.S. Patent No. 4,466,738, issued to Huang et al..

29 A heretofore essentially unrelated field has been that
30 concerning the properties of wave mixing within a
31 photorefractive crystal. Various adaptations and applications
32 concerning this property have been devised, such as that
33 disclosed in U.S. Patent No. 4,703,992, issued to Yeh. Wave
34 mixing occurs when, in a crystal, two intersecting laser
35 beams form an intensity interference pattern which creates a
36 refractive index grating via the electro-optic effect in the
37 photorefractive crystal. The grating is a periodic
38 variation in the index of refraction of the crystal.

1 It happens that, in conventional two wave-mixing,
2 vibrations in the laser beam and the crystal cause transient
3 variation in the effective gain, which results in fading and
4 distortion in an output signal. Therefore, it has been
5 thought that no useful signal could be derived from the wave
6 mixing property inherent in photorefractive crystals which
7 could be useful for accurately and reliably providing an
8 output signal modulated according to vibrations of the
9 crystal.

10 Clearly, if the wave mixing properties of a crystal
11 could be utilized to provide an output modulated by
12 vibration of the crystal, then there would be attendant
13 advantages. Among the advantages would be the inherent
14 precision of measurement of the laser interferometric
15 principles involved, and the ability to produce a small and
16 rugged vibration sensor the output of which could be
17 transmitted through optical fibers to detector apparatus.
18 However, the instabilities associated with wave mixing have
19 reduced the usefulness of the application of this principle
20 such that, to the inventor's knowledge, nor prior art method
21 has been developed to sense vibrations in a crystal using
22 wave mixing principles.

23 No prior art, to the inventor's knowledge, has
24 successfully provided a stable laser output modulated by
25 vibrations in a crystal, and all previous applications have
26 resulted in output signals which suffer from unwanted
27 distortion and fading.

28 29 SUMMARY OF THE INVENTION

30 Accordingly, it is an object of the present invention
31 to provide a vibration sensor that is accurate and reliable
32 in operation.

33 It is another object of the present invention to
34 provide a vibration sensor that can be placed in a small
35 package.

36 It is still another object of the present invention to
37 provide a vibration sensor which provides a stable output
38 signal.

1 It is yet another object of the present invention to
2 provide a vibration sensor which takes advantage of the
3 inherent accuracies of laser interferometry for detecting
4 vibration.

5 It is still another object of the present invention to
6 provide a vibration sensor which can be placed at a remote
7 location and information sent therefrom by means fiber optic
8 transmission.

9 Briefly, the preferred embodiment of the present
10 invention is a vibration sensor which utilizes wave-mixing
11 properties of coherent laser beams in a photorefractive
12 crystal. Vibrations of the crystal, itself, are what is
13 detected by the laser beams. Vibrations of the crystal
14 cause two intersecting laser beams to form an intensity
15 interference pattern which creates a refractive index
16 grating via the electro-optic effect in the photorefractive
17 crystal. Energy transfers from one beam to the other, thus
18 amplifying one beam at the expense of the other. The beam
19 coupling gain coefficient is dependent not only upon the
20 crystal properties, but also on externally applied
21 electrical and mechanical forces on the crystal. A
22 vibrational force on the crystal perturbs the position and
23 the velocity of the interference pattern relative to the
24 quasi-stationary grating within the crystal. The
25 redistribution of the internal charges in the crystal
26 modulates the gain coefficient and, thereby, intensity
27 modulates both beams. With no external bias on the crystal,
28 the vibration signal in a two-wave mixing geometry is highly
29 unstable, whereas the vibration signal remains stable in a
30 "four-wave" mixing geometry. Problems inherent in two wave
31 mixing can be minimized by applying a velocity bias to the
32 crystal. Such bias can be applied externally, as for
33 instance by Doppler shifting either of the input laser beams
34 or by applying an electrical bias field to the crystal
35 itself, and such methods for accomplishing the bias are
36 within the scope of the present invention. However, in the
37 best presently known embodiment of the invention the bias is
38 created internally within the crystal by operation of retro-

1 reflecting one of the laser beams back into the crystal in a
2 "four-wave" mixing geometry. Internal biasing can be
3 performed best, for example, in a 4-mm class crystal, when
4 the two primary laser beams mix contra-directionally in the
5 C axis orientation of the crystal.

6 An advantage of the present invention is that it
7 provides stable operating conditions such that the wave
8 mixing properties of a crystal can be utilized as a
9 vibration sensor.

10 A further advantage of the present invention is that
11 signal fading and harmonic distortion within the crystal are
12 minimized.

13 Yet another advantage of the present invention is that
14 information can be transmitted from the vibration sensor by
15 means of a fiber optic line.

16 Still another advantage of the present invention is
17 that a very accurate means of modulation a signal according
18 to vibrations is provided.

19 Yet another advantage of the present invention is that
20 a vibration sensor according to the present invention can be
21 put into a very small package.

22 Still another advantage of the present invention is
23 that a vibration sensor according to the present invention
24 is rugged and reliable in operation.

25 These and other objects and advantages of the present
26 invention will become clear to those skilled in the art in
27 view of the description of the best presently known mode of
28 carrying out the invention and the industrial applicability
29 of the preferred embodiment, as described herein and as
30 illustrated in the several figures of the drawing.

31 32 BRIEF DESCRIPTION OF THE DRAWING

33 Fig. 1 is non-linear optical crystal vibration sensing
34 device, according to the present invention;

35 Fig. 2 is a detail of a crystal, showing the
36 relationship of laser beams therein, according to the
37 present invention; and

38 Fig. 3 is a graphic representation of crystal gain

1 coefficient curves, showing the effect of velocity biasing,
2 according to the present inventive method.

3
4 DETAILED DESCRIPTION OF THE INVENTION

5 The best presently known mode for carrying out the
6 invention is a non-linear optical crystal vibration sensing
7 device 10 having a HeNe laser 12 which outputs therefrom a
8 coherent light beam 14 through an isolator 16. The isolator
9 16 is a conventional device which prevents feedback into the
10 laser 12, which would otherwise cause instability in the
11 operation of the laser 12. The coherent light beam 14 then
12 passes into a beam splitter 18 which splits the coherent
13 light beam 14 into a first laser beam 20 and a second laser
14 beam 22. The second laser beam 22 is redirected by a first
15 mirror 24 into and through a photorefractive crystal 26.
16 The first laser beam is redirected by a second mirror 28
17 into and through the crystal 26. The two laser beams 20 and
18 22 interact within the crystal 26. Having passed through
19 the crystal 26, the first laser beam is counter-propagated
20 back upon itself as a third laser beam 30 by a retro-mirror
21 32. The third laser beam 30, again, passes through the
22 crystal 26, and is redirected by the second mirror 28 toward
23 the beam splitter 18.

24 The third laser beam 30 is then redirected by the beam
25 splitter 18 into a photodetector 34. As will be recognized
26 by one skilled in the art, in fact, only a portion of the
27 third laser beam 30 is redirected by the beam splitter 18
28 into the photodetector 34, and part of the third laser beam
29 30 will pass through the beam splitter 18 toward the laser
30 12. Indeed, this is the primary reason making desirable the
31 inclusion of the isolator 16 in the best presently known
32 embodiment 10 of the present invention since, without the
33 isolator 16, that portion of the third laser beam 30 which
34 passes through the beam splitter 18 toward the laser 12
35 might interfere with the stable operation of the laser 12.

36 The photodetector provides an electrical output 36
37 which may be provided to a wave analyzer (not shown) or to
38 an audio or visual detection means, as may be appropriate to

1 the usage to which the non-linear optical crystal vibration
2 sensing device 10 is being applied.

3 In the best presently known embodiment 10 of the
4 invention, the crystal 26 is attached to a test object 38,
5 which, in the case of the example of Fig. 1, is a shaker
6 table. Vibrations in the test object are transferred to the
7 crystal 26 and modulate the third laser beam 30, as will be
8 described hereinafter. The test object 38, as used in
9 conjunction with the best presently known embodiment 10 of
10 the present invention, is representative of any body to
11 which the crystal 26 may be attached for sensing vibrations
12 and/or other movement therein.

13 Also provided in the best presently known embodiment 10
14 of the present invention is a partially reflective mirror 40
15 intersecting the path of the second laser beam 22, as
16 illustrated in Fig. 1. Appearance of a phase conjugate beam
17 42, as illustrated, will assure proper alignment of the
18 crystal 26 and the laser beams 20, 22 and 30. The phase
19 conjugate beam 42 is produced within the crystal 26, as will
20 be described in more detail, hereinafter.

21 Fig. 2 is a detailed drawing of the photorefractive
22 crystal 26 of Fig. 1. The crystal 26 of the best presently
23 known embodiment 10 of the present invention is a BaTiO_3
24 crystal, of the 4-mm class, although other crystal might be
25 used to practice the invention. As will be described in
26 more detail, hereinafter, optimal conditions are achieved
27 when the laser beams 20 and 22 are mixed contra-
28 directionally generally along a "C" axis 44 of the BaTiO_3
29 crystal 26. It should be noted that the position of the
30 laser beams 20, 22 and 30 in relation to the crystal 26 and
31 the "C" axis 44 thereof, as depicted in Fig. 2, are
32 illustrative only, and the effects of those relationships
33 will be discussed in more detail, herein. One skilled in
34 the art will be familiar with the general requirements for
35 wave mixing, including the coherency of the laser beams to
36 be mixed.

37 As can be seen in the view of Fig. 2, refractive
38 properties of the crystal 26 cause the first laser beam 20

1 and the second laser beam 22 to refract as they enter the
2 crystal 26. In accordance with well known principles, the
3 first laser beam 20 and the second laser beam 22 also
4 refract again, generally to resume their original direction
5 of travel, as they leave the crystal 26. As will be
6 appreciated by one skilled in the art, a first grating 46
7 will be established by the mixing of the first laser beam 20
8 and the second laser beam 22. As is well known in the art,
9 a grating such as the first grating 46 is a periodic
10 variation in the index of refraction of the crystal 26,
11 which periodic variation is slow to change relative to
12 changes in the conditions which create it. The first
13 grating 46 is arrayed along a first grating plane 48. The
14 first grating plane 48 bisects the paths of the first laser
15 beam 20 and the second laser beam 22 through the crystal.

16 As previously discussed in relation to Fig. 1, the
17 retro-mirror 32 redirects the first laser beam 20 back upon
18 itself, and the redirected beam is referred to, herein, as
19 the third laser beam 30. A second grating 50 is formed by
20 mixing of the first laser beam 20 and the third laser beam
21 30. Since the first laser beam 20 has been turned directly
22 back upon itself by the retro-mirror 32, the third laser
23 beam 30 travels the same path through the crystal 26 as does
24 the first laser beam 20, except reversed 180° in direction,
25 forming the second grating 50. It should be noted that a
26 third grating 53 will be formed perpendicular to the first
27 grating 46 by the mixing of the second laser beam 22 and the
28 third laser beam 30.

29 A small fraction of the third laser beam 30 scatters
30 off of the first grating 46, which forms the phase conjugate
31 beam 42. However, most of the third laser beam 30 passes
32 back through the crystal 26 toward the photodetector 34.
33 Any vibration of the crystal perturbs the position of the
34 gratings 46, 50 and 53 with respect to the interference
35 pattern within the crystal 26, which results in intensity
36 modulation of the laser beams 20, 22 and 30. However, as
37 has been discussed heretofore, such modulation is generally
38 unstable, resulting in fading and harmonic distortion of the

1 modulation. Nevertheless, the inventor has found that the
2 portion of the third beam 30 which passes back through the
3 crystal 26 and exits toward the photodetector 34 (Fig. 1)
4 contains a modulation component that is stable and which
5 accurately represents vibration induced within the crystal
6 26. Such modulation is converted to the electrical output
7 signal 36 by conventional means within the photodetector 34.
8 The electrical output signal 36 can then be provided for
9 detection and/or analysis by any of the several conventional
10 means for detection and/or analyzing such electrical
11 signals.

12 Referring again to Fig. 2, a first beam angle 54 is the
13 angle between the first laser beam 20 and the "C" axis 44
14 within the crystal 26, and a second beam angle 56 is the
15 angle between the second laser beam 22 and the "C" axis
16 within the crystal. The inventor has found that vibrational
17 sensing stability is greatly enhanced, in the 4-mm class
18 crystal, when the first laser beam 20 and the second laser
19 beam 22 are mixed contra-directionally in the "C" axis 44 of
20 the crystal 26. This occurs when the first beam angle 54
21 approaches 0° and the second beam angle 56 approaches 180° .
22 However, to allow for the introduction of the retro-mirror
23 32, the second beam angle 56 is made a few degrees less than
24 180° in the best presently known embodiment 10 of the
25 present invention.

26 Fig. 3 is a graphic representation of gain coefficient
27 curves 58, showing the effect of velocity biasing in the
28 crystal 26 (Fig. 2), according to the present inventive
29 method, wherein the x axis represents velocity and the y
30 axis represents gain coefficient of the crystal 26. If, for
31 example, only two laser beams were mixed in a crystal (not
32 shown), which is referred to as two-wave mixing, a first
33 velocity bias point 60a of an unbiased gain coefficient
34 curve 58a is, nominally, at zero velocity, as is depicted in
35 the graph of Fig. 3. This is the condition referred to as
36 zero velocity bias. In this condition, an incoming physical
37 vibrational wave 62 (which, as has been discussed in detail
38 previously, herein, would physically vibrate the crystal 26

1 causing intermodulation of laser beams 20 and 22, therein)
2 would produce a harmonically distorted first output signal
3 64 of twice the frequency of the incoming physical
4 vibrational wave 62. Also, in this condition, varying
5 vibrations from uncontrolled background sources, and the
6 like, could give slight shifts in the velocity bias which
7 could contribute to fading and distortion of the first
8 output signal 64 as the sum of vibrations equilibrate to
9 zero velocity. A second gain coefficient curve 58b is shown
10 in a velocity biased position with a second velocity bias
11 point 60b at a non-zero position. As has been discussed
12 previously, herein, the inventor has found that, in the
13 velocity biased condition as depicted by the second gain
14 coefficient curve 58b, the incoming physical vibrational
15 wave 62 will cause vibrations in the crystal 26 which result
16 in an undistorted output signal 66. Furthermore, any slight
17 bias shift due to background sources will not degrade the
18 signal 66, since an operating bias point 68 is on the linear
19 portion of the gain coefficient curve 60b.

20 It is known in the art that a velocity bias can be
21 introduced into the crystal 26 (Fig. 2) by applying either
22 an electric field to the crystal 26 or by Doppler-shifting
23 the frequency of an incoming laser beam (not shown). As has
24 been previously discussed, herein, it is an aspect of the
25 present invention that such a velocity bias can produce the
26 undistorted output signal 66 when the crystal 26 is vibrated.
27 It is another aspect of the present invention that such a
28 velocity bias can be internally generated in the crystal 26,
29 without resorting to an external electric field or Doppler
30 shift, by counter-propagating one of the laser beams 20
31 (Fig. 2) in a four-wave mixing geometry, as has previously
32 been discussed in relation to Fig. 2. This is accomplished
33 because internally created space-charge fields from the two
34 major gratings 46 and 53 contribute a significant component
35 of field onto the counter-propagating grating 50 which, in
36 turn, provides for the velocity bias shift, as depicted in
37 the shifted gain coefficient curve 60b of Fig. 3.

38 As is shown above, in great part, the non-linear

1 optical crystal vibration sensing device 10 according to the
2 present invention utilizes the known phenomenon of wave
3 mixing in a heretofore unknown way to perform a function
4 that has previously been thought inappropriate to the
5 technology. Among the substantial differences are the
6 inclusion of a velocity bias which, in the best presently
7 known embodiment 10 of the invention is provided by the
8 geometry and arrangement of the laser beams 20, 22 and 30
9 within the crystal 26, as described herein. Further among
10 the substantial differences between the present invention
11 and the prior art is the method of producing the velocity
12 bias, as described herein. The components of the best
13 presently known embodiment 10 of the present invention are
14 commonly available, and no significant changes of materials
15 are envisioned nor are any special constructions required.

16 Various modifications may be made to the invention
17 without altering its value or scope. For example, while the
18 best presently known embodiment of the invention utilizes an
19 internal bias created within the crystal 26 by the laser
20 beams 20, 22 and 30, any means for introducing a velocity
21 bias might be utilized to achieve the purpose. Another
22 change which might be made to the invention would be to
23 substitute a different type of crystal for the class 4-mm
24 crystal utilized in the best presently known embodiment 10
25 of the present invention, although changes in the geometries
26 of the invention might be required to do so.

27 All of the above are only some of the examples of
28 available embodiments of the present invention. Those
29 skilled in the art will readily observe that numerous other
30 modifications and alterations may be made without departing
31 from the spirit and scope of the invention. Accordingly,
32 the above disclosure is not intended as limiting and the
33 appended claims are to be interpreted as encompassing the
34 entire scope of the invention.

35 36 INDUSTRIAL APPLICABILITY

37 The non-linear optical crystal vibration sensing device
38 10 is intended for use in a variety of vibration sensing

1 applications, such as contact microphones, accelerometers,
2 velocimeters, hydrophones and seismometers. The non-linear
3 optical crystal vibration sensing device can be placed in a
4 small package, having a face of approximately one square
5 centimeter, or even less. Therefore, it is anticipated that
6 it will be particularly useful in remote sensors, especially
7 where it is desirable that signal be carried from the sensor
8 by means of fiber optic cables, such that electronic
9 components can be placed at some distance from the source of
10 vibration. The non-linear optical crystal vibration sensing
11 device 10 can be substituted for other motion transducers in
12 many applications wherein high precision is desired.

13 Since the non-linear optical crystal vibration sensing
14 device 10 can be constructed such that there are no
15 electronic components at the sensor site, it is anticipated
16 that it will be particularly useful in applications wherein
17 localized electronic components are either undesirable or
18 inoperable, such as in explosive atmospheres, or where
19 electromagnetic interference might disrupt the operation of
20 electronic components, and the like.

21 The non-linear optical crystal vibration sensor 10 may
22 be utilized in any application wherein conventional
23 vibration sensors are used, and will provide increased
24 sensitivity and accuracy as compared to comparable prior art
25 devices. Therefore, it is expected that it will be
26 acceptable in the field as a substitute for the conventional
27 vibration and acceleration sensors. For these and other
28 reasons, it is expected that the utility and industrial
29 applicability of the invention will be both significant in
30 scope and long-lasting in duration.

NON-LINEAR OPTICAL CRYSTAL VIBRATION SENSING DEVICE

ABSTRACT OF THE DISCLOSURE

A non-linear optical crystal vibration sensing device (10) including a photorefractive crystal (26) and a laser (12). The laser (12) produces a coherent light beam (14) which is split by a beam splitter (18) into a first laser beam (20) and a second laser beam (22). After passing through the crystal (26) the first laser beam (20) is counter-propagated back upon itself by a retro-mirror (32), creating a third laser beam (30). The laser beams (20, 22, 30) are modulated, due to the mixing effect within the crystal (26) by vibration of the crystal (30). In the third laser beam (30), modulation is stable and such modulation is converted by a photodetector (34) into a usable electrical output, intensity modulated in accordance with vibration applied to the crystal (26).

Fig. 1

Fig. 2

Fig. 3

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