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(54) Title: LASER INTERFEROMETER

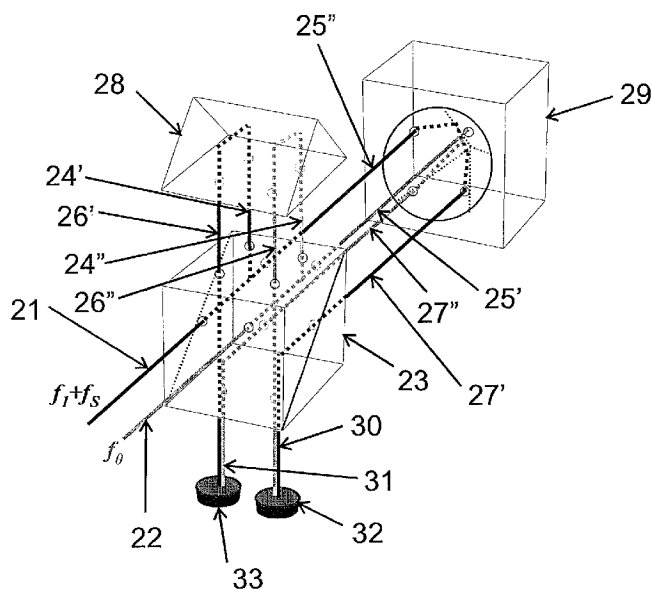


Fig. 2

(57) Abstract: Laser interferometer comprising a laser light source providing at least one light beam at two distinct frequencies, a beam splitter for splitting the at least one light beam into reference and measurement beams, a first reflector and a second reflector for reflection of the reference and measurement beams, and at least one detector for detection of the interference signal pertaining to the reflected reference and measurement beams. The laser light source provides first and second light beams that are spatially separated and the first light beam has a first of said two distinct frequencies and the second light beam has a second of said distinct frequencies. Further the beam splitter splits the first and second light beams into first and second spatially separated reference beams travelling to the first reflector, and into first and second spatially separated measurement beams travelling to the second reflector. One of the first and second reflectors is arranged to cause that the reflected first measurement beam shares at least part of a travelling path with the second reflected reference beam and that the reflected second measurement beam shares at least part of a travelling path with the first reflected reference beam.

Laser interferometer

The invention relates to a laser interferometer comprising at least one laser light source providing at least one light beam at two or more distinct frequencies, a beam splitter for splitting the at least one light beam into reference and measurement beams, a first reflector and a second reflector for reflection of the reference and measurement beams, and at least one detector for detection of an interference signal pertaining to the reflected reference and measurement beams.

Such a laser interferometer is known from US-B-6,847,455.

Figure 1 shows a typical setup of a laser interferometer according to the prior art. A beam originating from a laser light source 1 which has light with coaxial, orthogonal polarizations and different optical frequencies, f_1 and f_2 , are split by a non-polarizing beam splitter 2 (NPBS) into a reference signal 3 to be detected by a detector 4 and a measurement signal 5 that is transmitted to a polarizing beam splitter 6 (PBS). At the polarizing beam splitter 6 (PBS) a first light beam 7 having a first polarization and a first frequency f_1 is transmitted to a reference retroreflector 8 after passing a quarter-wave plate 9. After being reflected it passes with the appropriate polarization again the polarizing beam splitter 6 (PBS) and arrives after passing a polarizer 10 at the measurement photo-detector 11. Likewise at the polarizing beam splitter 6 (PBS) a second light beam 12 having a second polarization and a second frequency f_2 is transmitted to a measurement retroreflector 13 after passing a further quarter-wave plate 14. It then also passes after being reflected with the appropriate polarization again the polarizing beam splitter 6 (PBS) and arrives after passing the polarizer 10 also at the measurement photo-detector 11.

This prior art heterodyne laser interferometer has been widely used as a precise tool for measuring displacements in the fields of science and industry because of its high dynamic range, and high signal-to-noise ratio. To achieve nanometer or sub-nanometer level of reliability and accuracy with this type of laser interferometer, several error factors have to be taken into account and suppressed in order to secure the required accuracy. Particularly a periodic or nonlinearity error caused by frequency mixing, polarization mixing and ghost reflections lim-

its the accuracy of the known interferometer because it deteriorates the purity of the interference signals stemming from the interference of the measurement and reference beams with frequencies f_1 and f_2 .

5 In the article 'Acousto-optic displacement-measuring interferometer: a new heterodyne interferometer with Angstrom-level periodic error', published in Journal of Modern Optics 49, pages 2105-2114, by T.L. Schmitz and J.F. Beckwith it is proposed to provide the known heterodyne laser interferometer with
10 an acousto-optic modulator as a beam splitter. The diffraction angle of the acousto-optic modulator is however very small and the acousto-optic modulator is likely to have frequency mixing due to manufacturing imperfections. Its specific configuration limits the typically possible applications for measuring dis-
15 placements. This device corresponds to what is known from US-B-6,847,455.

It is an object of the invention to provide a broadly applicable heterodyne interferometer which has no significant periodic errors, has improved resolution and which has a simple
20 configuration and can be manufactured at acceptable costs.

The laser interferometer according to the invention has to this end those features as are enumerated in one or more of the appended claims.

In a first aspect of the invention the laser interferometer has the feature that the laser light source provides
25 first and second light beams that are spatially separated and wherein the first light beam has a first of two distinct frequencies and the second light beam has a second of said distinct frequencies, and further that the beam splitter splits the first
30 and second light beams into first and second spatially separated reference beams travelling to a first reflector, and into first and second spatially separated measurement beams travelling to a second reflector, and that one of the first and second reflectors is arranged so as to cause that the reflected first measurement beam shares at least part of a travelling path with the
35 reflected second reference beam and that the reflected second measurement beam shares at least part of a travelling path with the reflected first reference beam. Due to the complete spatial separation of the first light beam and the second light beam
40 with the distinct frequencies, the problem of leakage of light fractions from one beam into the other beam is effectively

avoided, and consequently periodic errors due to frequency and polarization mixing are significantly reduced.

The laser interferometer according to the invention provides the benefit that the first and second light beams may have the same polarization. The use of polarization filters is therefore unnecessary.

Furthermore instead of using a polarizing beam splitter as in the prior art, it suffices that the beam splitter is a non-polarizing beam splitter.

To promote the benefits of the invention it is further preferred that the reflected first measurement beam and the reflected second reference beam coincide in a first travelling path ending at a first detector, and that the reflected second measurement beam and the reflected first reference beam coincide in a second travelling path that is spatially separated from the first travelling path and ends at a second detector. The first detector and the second detector are most commonly photo detectors which thus provide two beat signals with a frequency that is the difference of the frequencies of the original first and second light beams. The signals at these two photodetectors have the same amplitude, however have an opposite phase-shift proportional to motions of any one of the reflectors, which provides an increased sensitivity for displacement of the second reflector that reflects the measurement beams.

Preferably the second reflector is a retroreflector.

It is further preferred that the first reflector for the first and second reference beams is one selected from the group comprising a prism, and mirrors.

The invention will hereinafter be further elucidated with reference to the drawing, showing in

- figure 1 a heterodyne laser interferometer according to the prior art;

- figure 2 a preferred embodiment of the heterodyne laser interferometer according to the invention;

- figure 3 an application of the laser interferometer of figure 2, wherein three distinct light frequencies are employed;

- figure 4 the laser interferometer of figure 2 shown in a two-dimensional schematic drawing; and

- figures 5-10 several embodiments of measurement-devices incorporating the laser interferometer of the invention.

The heterodyne laser interferometer according to the prior art has been discussed hereinabove with reference to figure 1. Further discussion of this prior art laser interferometer can therefore be dispensed with.

Figure 2 shows the preferred embodiment of a basic embodiment of the heterodyne laser interferometer of the invention. There are in this interferometer two parallel light beams 21, 22 from an optical source (not shown), which may have the same polarization and which are embodied with frequencies f_0 and $f_0 + f_S$ respectively. These two light beams 21, 22 propagate to a non-polarizing beam splitter 23 (NPBS) where these two beams 21, 22 are split into reference beams 24', 24'' and measurement beams 25', 25''. The two reference beams 24', 24'' are reflected by 90° to a right angle prism 28 where they are reflected into reflected reference beams 26', 26''. The two measurement beams 25', 25'' propagate to the retroreflector 29 where they are reflected into reflected measurement beams 27', 27''.

The retroreflector 29 is arranged such that the first measurement beam 25'' and the second measurement beam 25' that originate from the first light beam 21 and the second light beam 22 respectively, cross each other while they are reflected. This causes that the reflected first measurement beam 27' -that originates from the first light beam 21- shares eventually at least part of a travelling path 30 with the reflected second reference beam 26'' -that originates from the second light beam 22-, and correspondingly that the reflected second measurement beam 27'' -that originates from the second light beam 22- shares eventually at least part of a travelling path 31 with the reflected first reference beam 26' that originates from the first light beam 21. This sharing or coinciding of travelling paths could of course also be occasioned by having the first reference beam 24' and second reference beam 24'' cross each other at the first reflector 28 whilst maintaining the spatial position of the reflected measurement beams at the retroreflector 29 unmended. This is not shown in the preferred embodiment but is clear to the artisan and requires no further elucidation or explanation.

The shared travelling paths 30, 31 of the measurement beams with the reference beams are positioned behind the non-polarizing beam splitter 23 to which the reflected measurement beams 27', 27'' return after being reflected by the retroreflec-

tor 29. At the end of the said shared or coinciding travelling paths 30, 31 the laser interferometer is provided with appropriate photodetectors 32 and 33 for detection of the beat frequency caused by the sharing of the measurements beams and reference beams at their final approach of said photodetectors 32, 33 along said coinciding travelling paths 30, 31.

When the retroreflector 29 is moving, the reflected measurement beams 27', 27'' are provided with a phase shift caused by a Doppler frequency shift that is measured by the photodetectors 32 and 33. In the laser interferometer of the invention the heterodyne signals from the photodetectors 32, 33 provide the same measurement amplitudes however having opposite signs of the phase shift. This is beneficial for the sensitivity of the displacement measurement of the retroreflector 29. It is found that the interferometer of the invention is insensitive to misalignment of the optical components, although attention is required for the initial alignment of the prism 28. This prism 28 can also be replaced by a set of mirrors or any other suitable type of reflection system.

Hereinafter the invention will be further elucidated with reference to the figures 3 - 10 relating to several measurement devices that incorporate the laser interferometer of the invention.

To increase the legibility of the figures pertaining to these embodiments, it is abstained from showing reference numerals, yet reference is made to the following legend:

Legend

RAP: right angle prism
NPBS: Non-polarizing beamsplitter
PBS: Polarizing beamsplitter
QWP: Quarter wave plate
LDBS: Lateral displacement Non-polarizing beamsplitter
M: mirror
RR: retroreflector (also known as a corner cube or cats eye)
 f_0 : frequency of the input beam
 f_s : frequency offset from the initial input beam's frequency
PD_r: reference photodetector
PD_m: measurement photodetector
B: optical block, essentially a plane plate.

Three mode laser application

Reference is first made to figure 3 relating to a three mode laser application of the interferometer.

5 Instead of using two optical frequency components as discussed hereinabove, three optical frequencies ($f_1 < f_0 < f_2$) can be used in the interferometer to improve the measuring resolution. In this case, one beam has two distinct frequencies (f_1 and f_2) and the other beam has only one frequency (f_0). When
10 these signals interfere, a secondary beat frequency is created [$(f_0 - f_1) - (f_0 - f_2)$] which doubles the overall resolution in the interferometer. By stabilizing this signal prior to sending the beams to the interferometer, and selecting a source with the appropriate frequencies, this second beat frequency can be de-
15 tected using PD1 and PD2. From PD₁ and PD₂, the interference signal can be described as

$$I_1 \approx \cos[2\pi(f_2 - f_0) - \phi_D] + \cos[2\pi(f_0 - f_1) + \phi_D] + \cos[2\pi(f_2 - f_1)] \quad (1)$$

$$20 \quad I_2 \approx \cos[2\pi(f_2 - f_0) + \phi_D] + \cos[2\pi(f_0 - f_1) - \phi_D] + \cos[2\pi(f_2 - f_1)] \quad (2)$$

The frequency differences, $(f_2 - f_1)$, $(f_0 - f_1)$, $(f_2 - f_1)$ are typically high frequency components larger than a few hundreds
25 of MHz when using 3 longitudinal mode He-Ne lasers or diode lasers. Consequently they can not be measured with slow detectors which have a bandwidth below 10 MHz.

However, the second beat frequency components can be detected with low-bandwidth detectors and they are derived from Eq.(1)
30 and (2) as

$$I_{S1} \approx \cos[2\pi(f_2 + f_1 - 2f_0) - 2\phi_D] \quad (3)$$

$$35 \quad I_{S1} \approx \cos[2\pi(f_2 + f_1 - 2f_0) + 2\phi_D] \quad (4)$$

Consequently, the phase difference between two second beat frequency signals becomes $4\phi_D$ which means that the measurement resolution is enhanced comparing to the basic embodiment of
40 the interferometer of the invention by a factor 2.

One-dimensional measurement

In order to provide a reference for the variations of the basic embodiment of the laser interferometer of the invention that will be discussed hereinafter, the basic embodiment shown in figure 2 is again shown in figure 4 in a schematic two-dimensional drawing of the laser interferometer. This interferometer is particularly suited for one-dimensional displacement measurement (Fundamental setup). It has the following advantages:

1. There are no significant periodic errors. When a frequency decoupled laser source is used, this interferometer has no periodic errors, which is a significant improvement over other interferometer configurations.
2. This interferometer has the resolution of the moving RR enhanced by a factor 2. Single pass interferometers normally have an optical resolution of 2, whereas this interferometer has an optical resolution of 4.
3. Simple configuration. Most heterodyne interferometers comprise more components, particularly the more costly polarizing components. These components contribute to the non-linearity due to imperfections and misalignments. That makes a prior art interferometer costly to develop and meticulous alignment must be performed. The interferometer of the invention does not have to deal with these issues, except for the RAP initial alignment.
4. Since the interferometer of the invention has no significant periodic errors when compared to systems of the prior art, the displacement information can be obtained directly and much faster than with prior art systems. Those systems require extra initial movement and/or calculation time for determining and correcting the periodic nonlinearities. Because the interferometer of the invention does not require this, it is more suitable for real-time applications.
5. Not sensitive for alignment errors of the polarisation direction of the laser beams relative to the optics.

Further considerations

1. The RAP is not tilt sensitive which means its initial align-

ment is critical and the tolerances on the 90 degree angle are quite strict. However, these tolerances are in line with what a prior art interferometer requires.

2. The two input beams need to be parallel otherwise this contributes a small cosine error. However, when the displacement is determined from the phase difference, this just adds an extra scaling factor once calibrated for.

Angle measurement

Figure 5 shows a variation to the laser interferometer of figure 2 and figure 4 which can be used to measure the tilt angle between its two movable retroreflectors RR. The retroflectors RR are tilt insensitive for alignment purposes. However, if both are attached to the same moving stage, then the in-plane tilt of that stage can be determined. Additionally, if f_s is known and measured concurrently, the displacement can also be determined.

Two spatially separated, parallel beams are used as the source in this interferometer. In the figure, the dotted beams refer to the beam that is below the solid beam. The two beams traverse to a NPBS at which point they are divided into two groups, one transmitted group and one reflected group. The reflected beam-set travels from NPBS to one of the retroreflectors RR (the top RR) after reflecting from a 90° Right angle prism. After reflecting from the top RR, which is fixed to the moving stage, the beams reflect back from the RAP and go back to the NPBS. At the same time, the transmitted beam-set goes through the block (B), which causes the beam positions to be exchanged with each other. The beam-set then goes to the other retroreflector RR, which is attached to the same moving stage as the top RR. After being reflected at this retroreflector, the beams travel back to the NPBS. The two beam-sets are interfered using the NPBS and each of the beams can be detected by each photodetector (PD_m and PD_r). The phase difference between the two signals provides a measure for the tilt angle.

Advantages

1. This interferometer has no significant periodic errors, due to eliminating the conventionally applied polarizing components.

2. As with the basic embodiment, this interferometer gains an additional optical resolution enhancement by a factor 2.
3. Because two retroreflectors are used, higher than normal tilt angles can be measured over much longer distances. Typically in the prior art a mirror is used for tilt sensitive interferometers because a retroreflector is tilt insensitive. However, when a mirror is used, the tilt combined with the displacement limits the range of the tilt. This is particularly magnified for longer displacement measurements. The interferometer of the invention does not have this typical limitation.

Further considerations

1. The interferometer of figure 5 requires an extra block (B), which is normally not used in an interferometer. However, manufacturing and alignment of this block is not problematic for the skilled person.

Tilt (angle) measurement using plane mirror setup

Figure 6 shows a further interferometer, which is an extension of the basic angle measurement interferometer of figures 2 and 4. In many applications, a moving stage needs to be controlled with six degrees of freedom. If the stage has large displacements in all 3 linear degrees of freedom, retroreflectors cannot be used because large lateral motions will cause a misalignment. In those cases, a plane mirror is the desired target on the motion stage.

Once again, in the interferometer of figure 6 two spatially separated, parallel beams are divided into two sets of beams. Each set of beams has a double path between polarizing beam splitter (PBS), quarter wave plate QWP and moving mirror (M_M). The measurement beams are reflected by the retro-reflector (RR), which has point symmetry, while the reference beams are reflected by the right angle prism (RAP), which has line symmetry. Two sets of beams go back to BS and are then recombined to make the heterodyne signals.

The main principle applied in the interferometer of figure 6 is the same as in the basic embodiment of the interferometer shown in figures 2 and 4; the measurement and reference phase

signals have opposite signs which doubles the resolution when the phase difference is taken. The phase difference between two signals gives the tilt angle. In the interferometer of figure 6, the optical resolution is $\lambda/8$ because of the double path interferometer setup and the principle as aforementioned.

Advantages

1. Like the other interferometers of the invention, the interferometer of figure 6 is designed to have minimal periodic errors. In the other embodiments no polarizing components were used. However, in this case, two are used (the QWP and the PBS). If the incoming beams are however completely separated without any mixing, then these components should minimally contribute to periodic errors.
2. The optical resolution of this interferometer is a factor $\lambda/8$. This means very precise measurements can be performed.

Further considerations

1. The right angle prism can be exchanged into a retro-reflector and a glass block and vice versa. Alternatively, 2 mirrors can be used.

Plane mirror interferometer

As mentioned with reference to the interferometer of figure 6, many interferometry applications require linear motions in all 3 degrees of freedom, meaning that a plain mirror must be used as a target. Figure 7 relates to such an interferometer target embodied as a plain mirror, instead of a retroreflector. Additionally, a PBS, QWP, and RR are used and attached to the NPBS.

The beam set transmitted from NPBS pass through the PBS and QWP, where they reflect at the mirror. On their way back, the beams pass through the QWP which causes them to reflect at the PBS. The beams reflect at the RR and the PBS again, where they pass through the QWP again on their second time travelling to the mirror. After reflecting at the mirror, the beams pass through the QWP and the PBS, where they interfere with beams from the RAP on the NPBS. The measurement result is insensitive

to tilting of the moving mirror and has an optical resolution $\lambda/8$.

Advantages

1. The interferometer of figure 7 is designed to have minimal periodic errors. This is largely due to the decoupled light beams that enter the interferometer, which reduces the periodic errors.
2. This interferometer has an optical resolution of 8, which is twice the normal resolution for a plane mirror interferometer. Also, like the plane mirror interferometer, this interferometer is insensitive to tilting of the moving mirror (for small angles).

Further considerations

1. As it is shown in figure 7, the optics are not thermally stable. However, this could be accomplished by adding an extra compensation block in between the RAP and the NPBS.

Differential plane mirror interferometer

The interferometer shown in figure 8 is exactly the same as the 'Tilt (angle) measurement interferometer with a plane mirror' as shown in figure 6, except that it does not measure the tilt but rather the displacement between two different mirrors. This is called a differential interferometer.

Advantages

1. Once again, this interferometer is designed to have minimal periodic errors. This is largely due to the decoupled incoming light beams that reduce the chance that periodic errors occur.
2. This interferometer has an optical resolution of 8, which is twice the normal resolution for a differential interferometer.
3. This interferometer is semi-balanced between measure-

ment and reference paths which reduces thermal errors.

Multi DOF displacement measurement

5 Many interferometers of the prior art are designed to combine measurements of one or more displacements and/or one or more angles into one configuration. This typically means that initially only the input beams and mirror are aligned and the rest of the alignment is done during the manufacturing process.
10 This makes interferometers adaptable to multi-degree of freedom measurements.

 The setup of the interferometer shown in figure 9 is the combination of a differential plane mirror interferometer and an angle measurement interferometer. In this interferometer,
15 PD_{R1} and PD_{M1} measure the displacement of the mirror while PD_{R2} and PD_{M2} measure the tilt angle of the mirror. The optical resolution is $\lambda/8$ because of the double path interferometer setup.

Advantages

- 20
1. Once again, this interferometer is designed to have minimal periodic errors due to the decoupled incoming light beams, which reduces periodic errors.
 2. This interferometer has an optical resolution of $\lambda/8$ for both
25 angular and lateral measurements

Straightness measurement

30 Figure 10 shows a setup of the laser interferometer of the invention that is usable for straightness measurements. This embodiment is based on the differential plane mirror interferometer of figure 8, but the measurement mirrors are replaced by
35 a prism (P) which can adjust the beam direction, and by a special mirror (M_S). When the mirror M_S moves along the horizontal axis (perpendicular to the arrow drawn), this interferometer can measure the vertical displacement with a resolution of $\lambda/8$.

Advantages

1. Also this interferometer of figure 10 is designed to have minimal periodic errors due to the decoupled incoming light beams, which reduce periodic errors.
2. This interferometer has an optical resolution of $\lambda/8$ for both angular and lateral measurements.

CLAIMS

1. Laser interferometer comprising one or more laser light sources providing at least one light beam at two or more distinct frequencies, a beam splitter for splitting the at least one light beam into reference and measurement beams, a first re-
5 flector and a second reflector for reflection of the reference and measurement beams, and at least one detector for detection of the interference signal pertaining to the reflected reference and measurement beams, **characterized in that** the laser light source provides first and second light beams that are spatially
10 separated and wherein the first light beam has a first of said distinct frequencies and the second light beam has a second of said distinct frequencies, and further that the beam splitter splits the first and second light beams into first and second spatially separated reference beams travelling to the first re-
15 flector, and into first and second spatially separated measurement beams travelling to the second reflector, and that one of the first and second reflectors is arranged so as to cause that the reflected first measurement beam shares at least part of a travelling path with the reflected second reference beam and
20 that the reflected second measurement beam shares at least part of a travelling path with the reflected first reference beam.

2. Laser interferometer according to claim 1, **characterized in that** the first and second light beams have the same polarization.

25 3. Laser interferometer according to claim 1 or 2, **characterized in that** the beam splitter is a non-polarizing beam splitter.

4. Laser interferometer according to any one of claims 1-3, **characterized in that** the reflected first measurement beam
30 and the reflected second reference beam coincide in a first travelling path ending at a first detector, and the reflected second measurement beam and the reflected first reference beam coincide in a second travelling path that is spatially separated from the first travelling path and ends at a second detector.

35 5. Laser interferometer according to any one of claims 1-4, **characterized in that** the second reflector is a retroreflector.

6. Laser interferometer according to any one of claims

1-5, **characterized in that** the first reflector for the first and second reference beams is selected from the group comprising a prism, and mirrors.

- 5 7. Method of using a laser interferometer according to any one of claims 1-6, **characterized in that** it employs light beams at three distinct frequencies, such that a first light beam has one of said frequencies and that a second light beam has the remaining two frequencies.

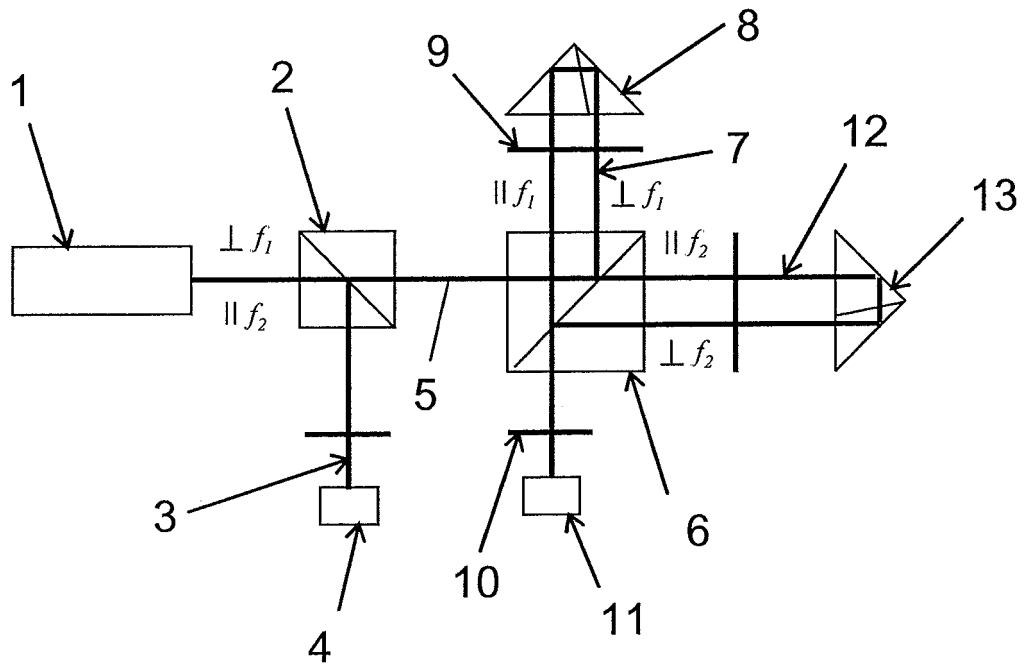


Fig. 1

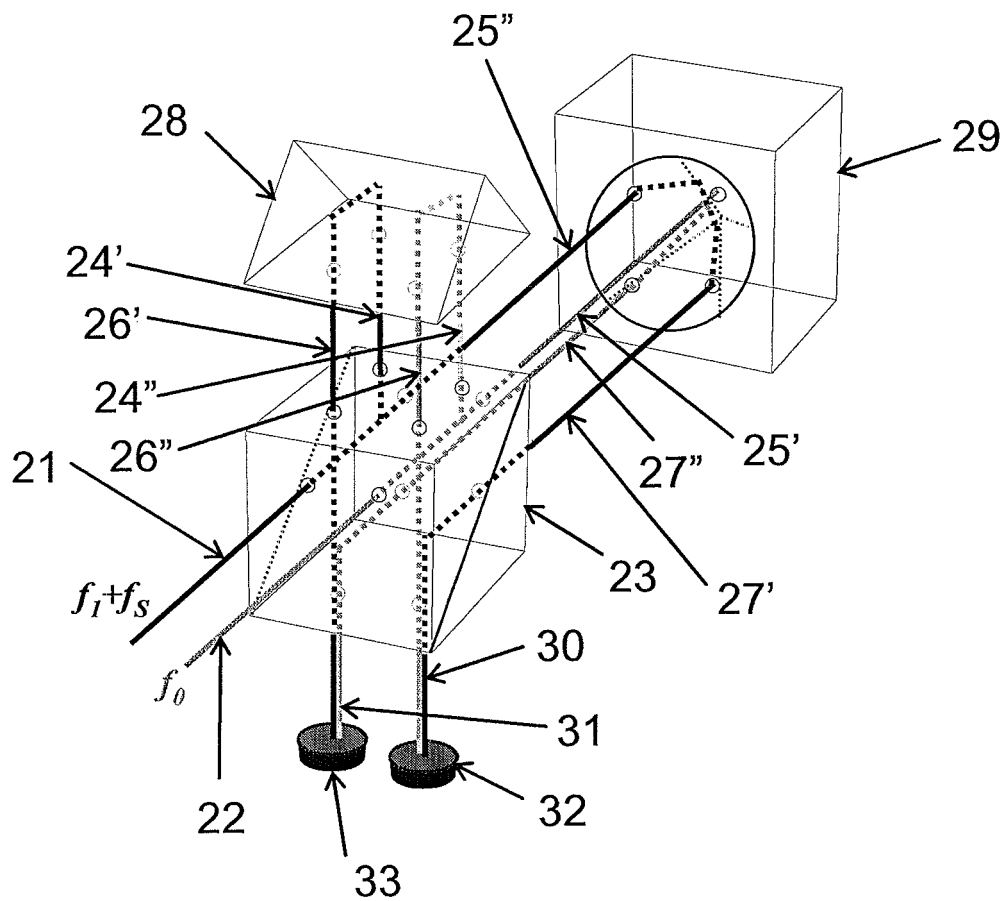


Fig. 2

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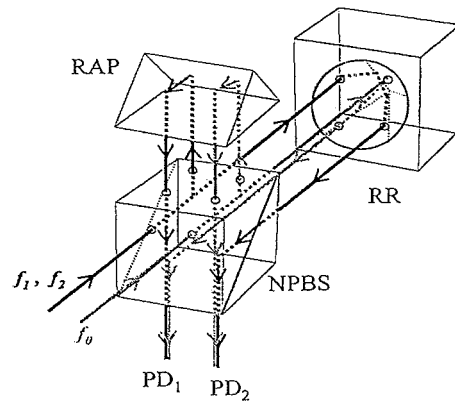


Fig. 3

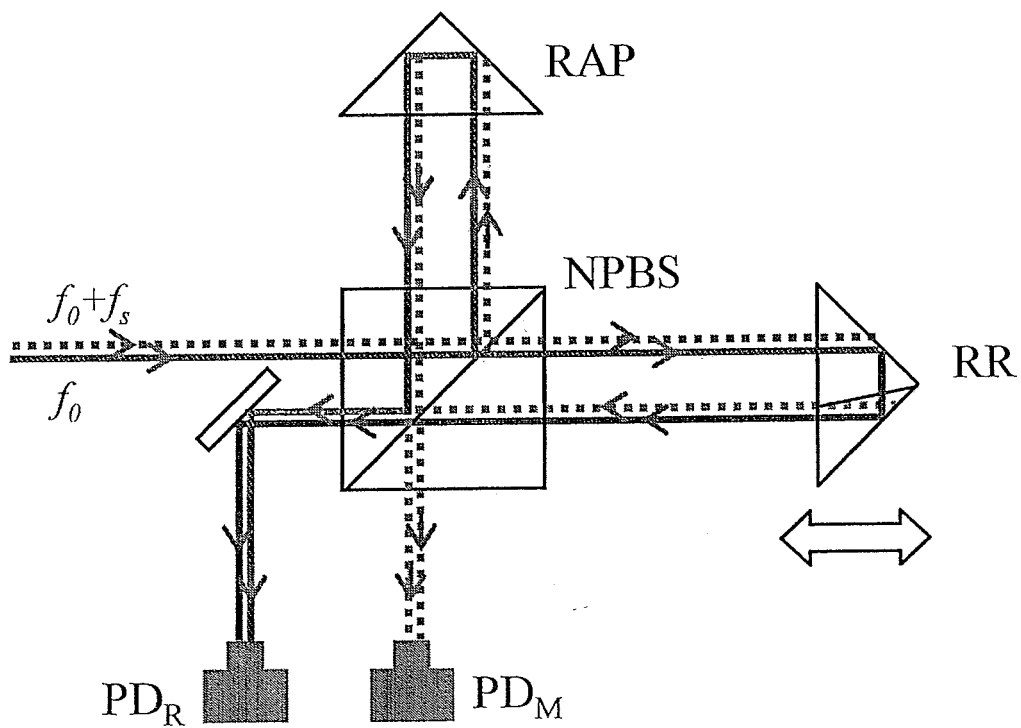


Fig. 4

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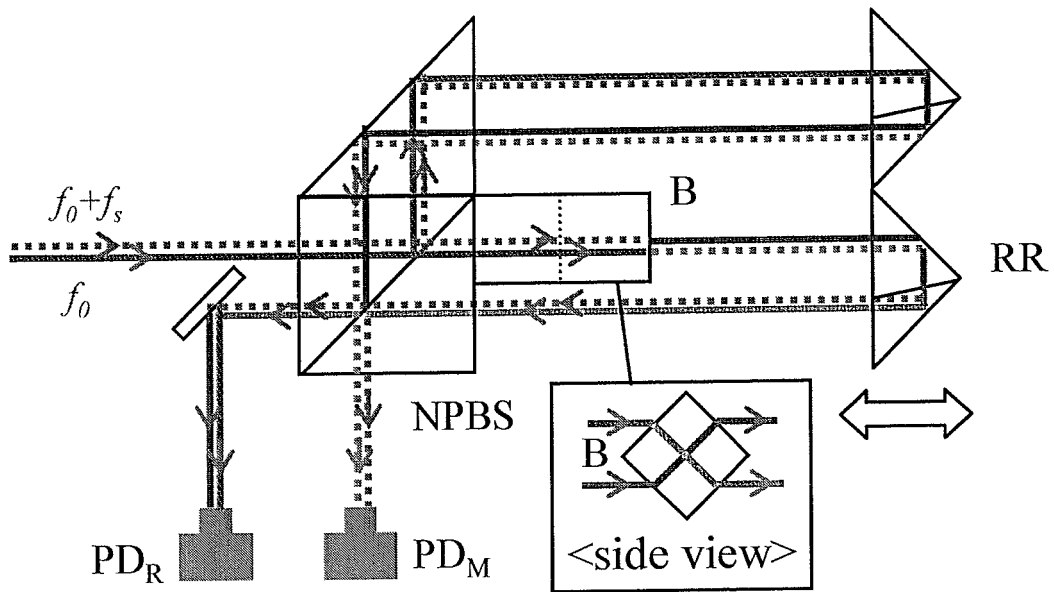


Fig. 5

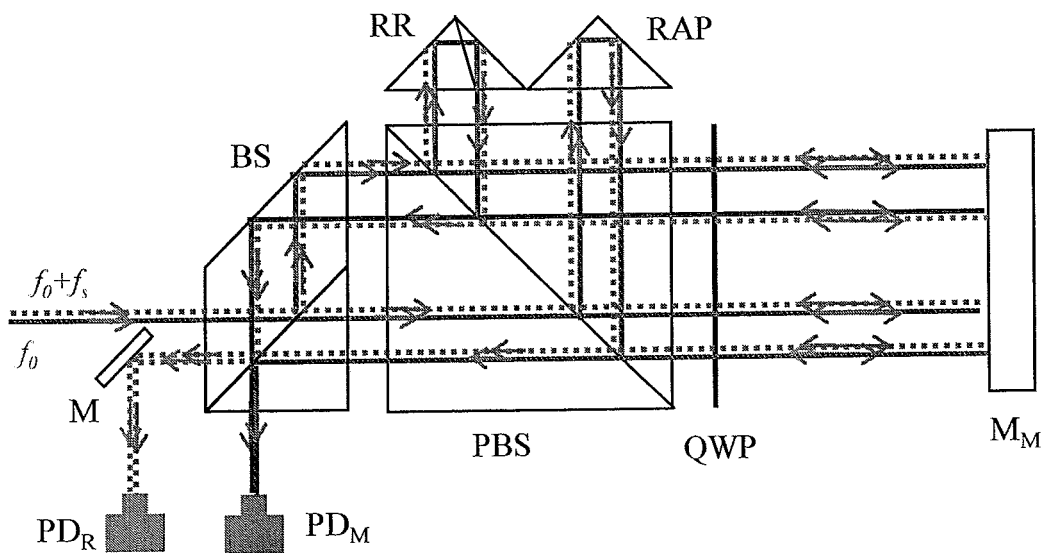


Fig. 6

5/6

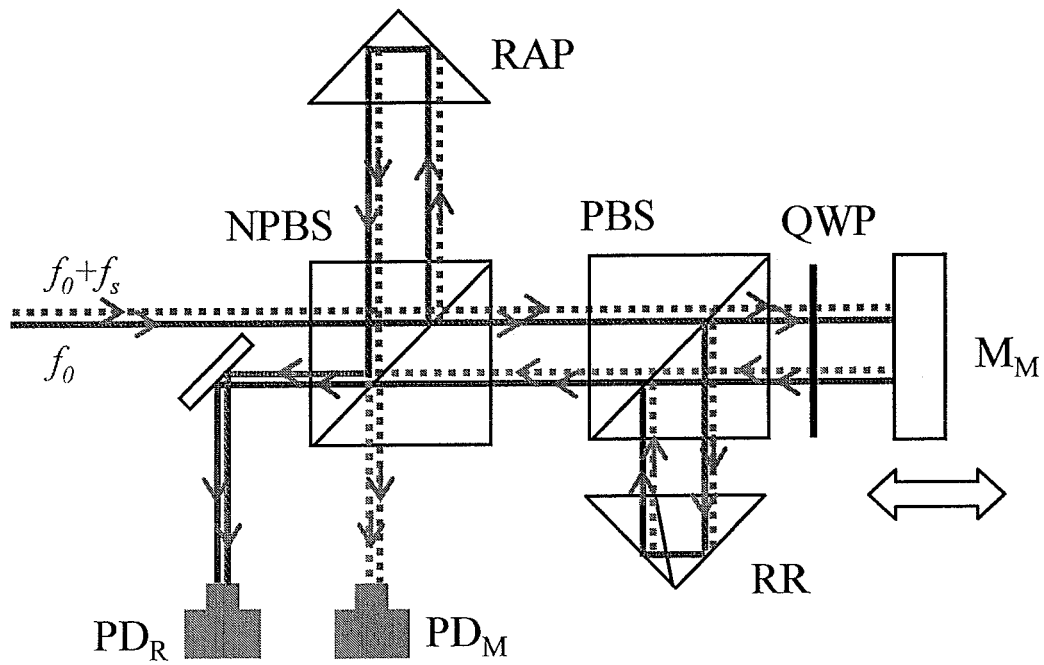


Fig. 7

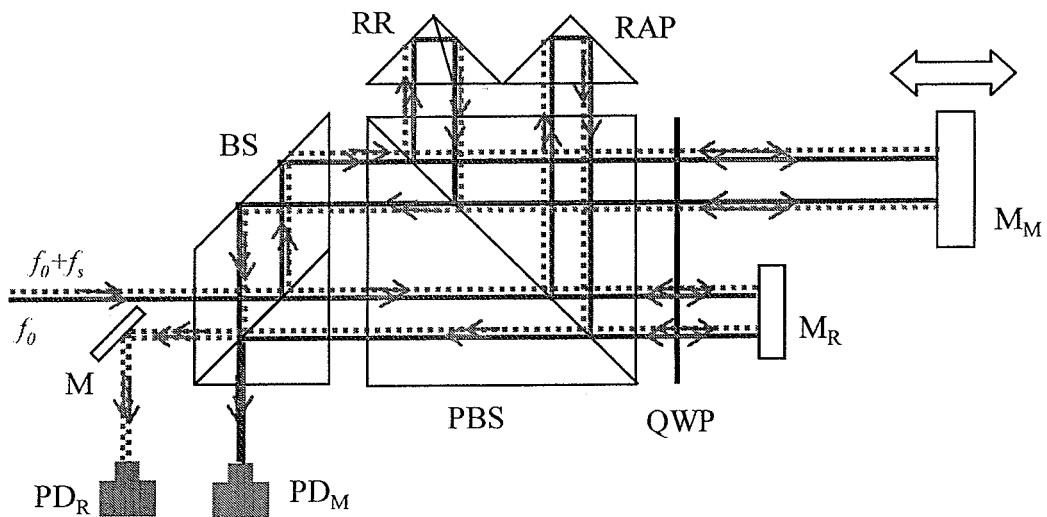


Fig. 8

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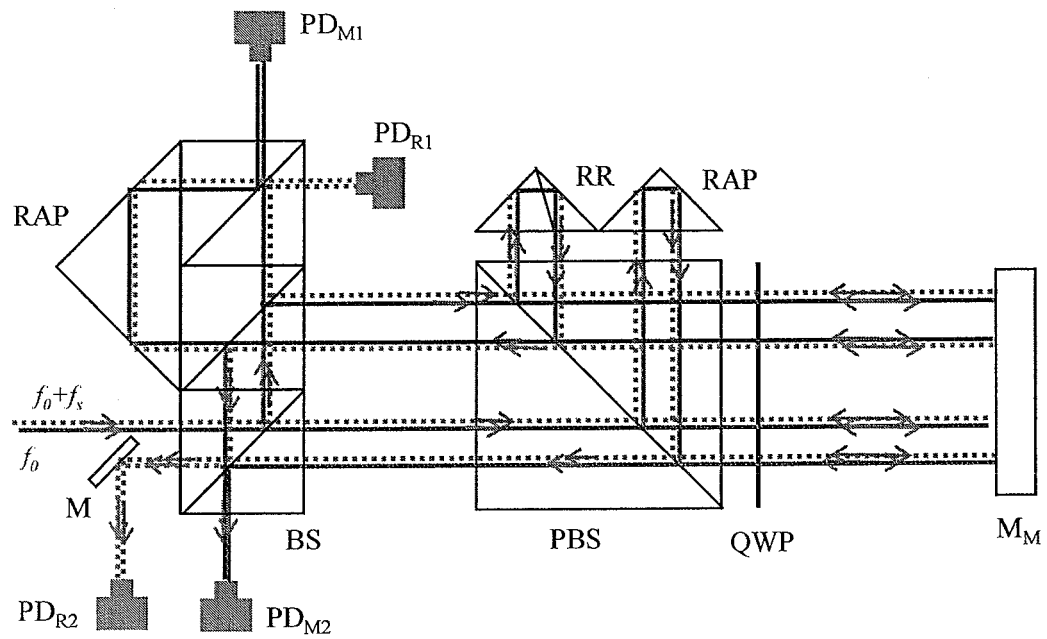


Fig. 9

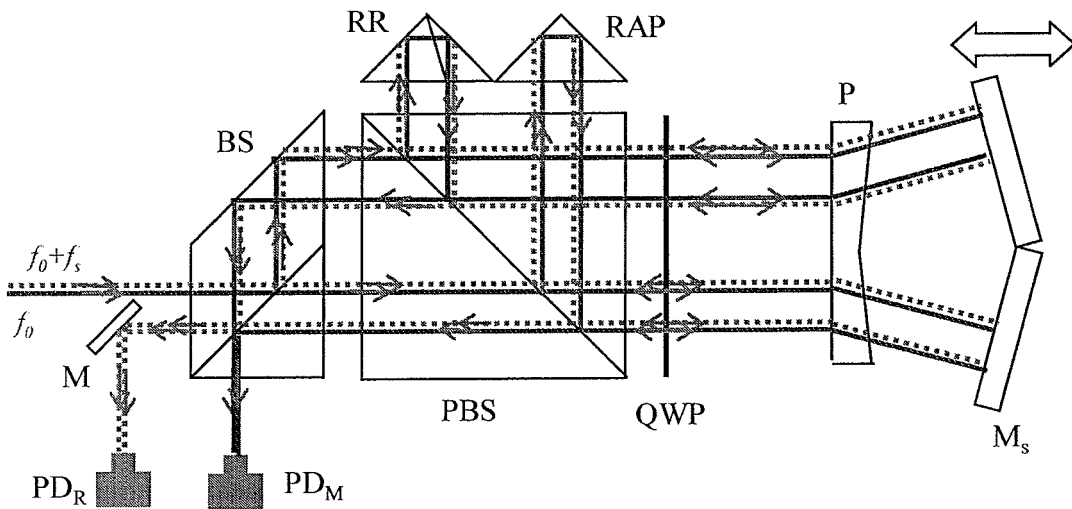


Fig. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2009/050541

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01B9/02 G01B11/02

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)
G01B

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 practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 483 593 B1 (BELL JOHN A [US] ET AL) 19 November 2002 (2002-11-19)	1-6
Y	column 5, line 24 - column 9, line 60; figures 1-4	7
X	US 4 717 250 A (SOMMARGREN GARY E [US]) 5 January 1988 (1988-01-05)	1
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Further documents are listed in the continuation of Box C.



See patent family annex.

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Information on patent family members

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