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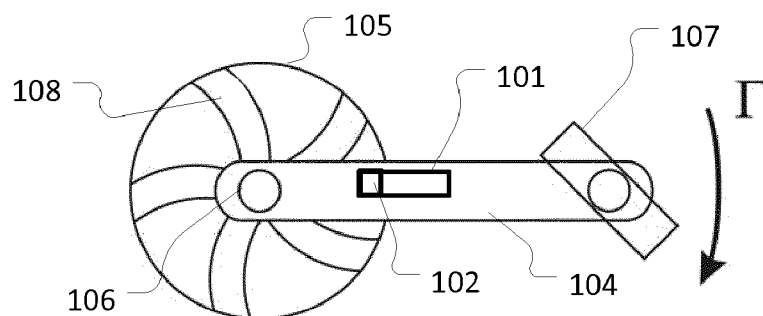


Fig. 1b

(57) Abstract: A bicycle power meter for measuring power generated when riding a bicycle, the power meter comprising a position-sensitive radiation detector (409) attachable to a component of a crank set (404) of bicycle, and a radiation source (408) attachable to the component of the crank set and configured to direct a radiation beam (410) towards the position-sensitive detector such that the radiation beam moves across the position-sensitive radiation detector when a torque (Γ) is applied to the component of the crank set.

Optical cycle power meter

Field of the invention

- 5 According to one aspect, this invention generally relates to cycle power meters. In another aspect, this invention relates to an optical deformation sensor for detecting a degree of bending or torsion/twisting of an object and, in particular, an optical deformation sensor for use in a cycle power meter.

10 Background of the invention

- There is a growing interest among cycle athletes to know the power generated when moving the bicycle forward. Knowing the power level allows the athlete to choose a power level that is just below the athlete's lactate threshold, thereby allowing the athlete to optimize his endurance during e.g.
15 a race or a training session. Furthermore, the power level is important during training for optimizing build-up of cardiac and muscle performance.

- Conventional cycle power meters are typically based on electro-mechanical strain gauges. WO 2009/006673 discloses a crank arm for a bicycle
20 comprising a hollow cavity in which strain gauges are mounted for measuring the torque-induced strain in the crank arm. It will be appreciated that, based on the strain measured with such a strain gauge, the applied torque Γ can be derived, which may further be converted into power P by using the relation $P = \Gamma \cdot \omega$, where ω is the angular velocity of the crank arm.

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US 6418797 discloses a hub-based cycle power meter in which strain gauges are mounted in the hub of the driving wheel. From the measured strain, the torque can be derived and thereby the power through multiplication with the angular velocity of the wheel.

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One disadvantage of the systems mentioned above is that the power meters are integrated in rather expensive cycle parts (such as the crank arm, the whole crank set or the hub), which means that the solutions get rather complex and expensive.

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One simpler power meter is described in US 2012/0214646 in which strain gauges are glued to an existing crank arm, i.e. a crank arm that is not modified to accommodate the power meter. However, the adhesion of strain gauges usually requires trained personnel and, hence, cannot be performed by a typical cyclist.

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It is an object of at least some embodiments of the present invention to provide a simple power meter that can be installed on an existing cycle part by an untrained cyclist.

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It is further an object of least some embodiments of the present invention to provide a deformation sensor that can be installed on an existing mechanical part of a dynamic device by an untrained person.

20 **Summary**

According to a first aspect, disclosed herein is a bicycle power meter for measuring power generated when riding a bicycle. Embodiments of the power meter comprise a deformation sensor for measuring bending or twisting of a component of a crank set of a bicycle responsive to a torque applied to said component, wherein the deformation sensor is attachable to said component as a deformation sensor unit and is configured to detect a deformation of said component in at least one bending plane, the deformation sensor comprising:

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- a support member attachable to said component, the support member defining a longitudinal direction in said bending plane;

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- a radiation source fixedly attached to the support member, wherein the radiation source is adapted to emit a radiation beam; and
- a position-sensitive radiation detector fixedly attached to the support member such that the radiation beam moves across the position-sensitive radiation detector when said support member is bent; and wherein the position-sensitive detector is operable to detect said movement.

Consequently, the deformation sensor unit is a very compact, stable unit that may be attached to the crank arm or other component. When the deformation sensor is provided as a single deformation sensor unit where the radiation source and the detector are fixedly attached to a support member, the deformation sensor is attachable to a component of the crank set as a single, pre-manufactured deformation sensor unit with the optical parts aligned and fixed with respect to one another during manufacturing. Consequently, the sensor unit may be installed at the bicycle by untrained personnel and without further alignment. Moreover, the cycle power meter may even be used interchangeably between different bicycles. The term "fixedly attached to the support member" in relation to a component of the deformation sensor is intended to include any form of mounting or integration where the component is directly or indirectly mounted to, or even integrated into, the support member such that displacement of the component relative to the support member is prevented.

Moreover, embodiments of the power meter are relatively insensitive to temperature changes, as the detector is configured to detect a bending or twisting/torsion of a component of the crank set, in particular an elongated component, e.g. a crank arm, responsive to an applied torque.

In some embodiments, the radiation source is adapted to emit a radiation beam along a direction transverse to said longitudinal direction and the deformation sensor unit comprises one or more optical elements fixedly

attached to the support member and configured to redirect the emitted radiation beam along the longitudinal direction and onto the position-sensitive radiation detector, such that the radiation beam moves across the position-sensitive radiation detector when said support member is bent. Hence, the sensor unit may be made very flat and compact such that it may easily be attached to a component of the crank set and that the risk of the sensor unit interfering with any moving parts during operation of the bicycle is reduced. Another advantage is that the light source and detector may be mounted on the same PCB, which makes production easier and which implies that the light source and detector are better fixed with respect each other.

The support member may be an elongated member having a longitudinal axis defining the longitudinal direction. In some embodiments, the support member is a flat plate or substrate defining the longitudinal direction within the plane of the plate or substrate. The transverse direction may be orthogonal or at least substantial orthogonal to the longitudinal axis. In some embodiments the transverse direction may be a direction pointing out of a plane defined by the support member, e.g. a direction normal to a surface of the support member.

Embodiments of the power meter require only a single deformation sensor unit mounted to a single part of the bicycle, e.g. a crank arm. It will be appreciated, however, that some embodiments of a power meter may comprise two deformation sensors attached to respective crank arms, thus allowing individual measurement of the torque applied via the respective pedals of the bicycle. This allows the power meter to independently measure the power generated by the left and right legs of the athlete, respectively.

Furthermore, various embodiments of the power meter disclosed herein may be used in combination with a variety of different materials of bicycle parts, e.g. with carbon-based or aluminum-based crank arms.

In some embodiments, the crank arm has a first end for attachment of the crank arm to a bottom bracket and a second end configured for attachment of a pedal to the crank arm, the crank arm defining a longitudinal direction
5 between the first and second ends. The sensor unit may be attached to the crank arm such that the position-sensitive radiation detector is positioned longitudinally displaced relative to the radiation source, and the position-sensitive radiation detector may be configured to detect a displacement of a position of the radiation beam within a detection area of the position-sensitive
10 radiation detector.

In particular, in some embodiments, the position-sensitive radiation detector and the radiation source are arranged to cause, responsive to a torque applied to the crank arm by an athlete during use of the bicycle, the radiation
15 beam to move across the position-sensitive radiation detector in a tangential direction relative to the rotation of the crank arm, and the position-sensitive radiation detector is adapted to detect the movement of the radiation beam along the tangential direction. Consequently, a bending of the crank arm in the radial-tangential plane relative to the axis around which the crank arm
20 rotates may reliably be detected with relatively large sensitivity. The torque applied by the athlete during use of the bicycle may be represented as a vector pointing in the axial direction defined by the crank axis.

In some embodiments, the power meter further comprises a signal
25 processing unit attachable to or integrated into a component of the crank set, e.g. the crank arm, and configured to receive a sensor signal from the position-sensitive radiation detector, wherein the signal processing unit comprises a communications interface for wireless communicating a measurement signal derived from the sensor signal. The wireless
30 communication may use any suitable wireless communication technology and protocol, such as the ANT+ protocol, Bluetooth, etc. . The signal

processing unit may be electrically powered by a battery or it may be powered, at least partly, by an energy harvesting system. This energy harvesting system may comprise a magnet attached to the bicycle frame which induces a voltage in an inductive coil attached to the crank arm or
5 another rotating component of the crank set, which charges either a capacitor or a battery, also attached to the crank arm or other component, which then powers the signal processing. Another energy harvesting means could be a piezoelectric system.

10 The signal processing unit may be integrated into the sensor unit or implemented as a separate unit. The signal processing unit may forward the sensor signal directly, thus rendering the measurement signal equal to the sensor signal, or process the sensor signal so as to obtain the measurement signal. For example, the signal processing unit may perform sampling,
15 averaging, noise-reduction and/or other signal processing functions. Alternatively, the signal processing unit may compute one or more quantities derived from the sensor signal, e.g. a power, and transmit the computed quantity or quantities. The power meter may comprise a housing accommodating at least one or more of the radiation source, the position-
20 sensitive radiation detector, the signal processing means, and a wireless communications circuit.

The power meter may further comprise a second processing unit, e.g. for attachment to the handle bar of the bicycle or at another convenient position.

25 The second processing unit is configured to receive the measurement signal, optionally to process the received signal, and to display the received and/or processed signal. The second processing unit may be any suitable processing device, such as a suitably configured bicycle computer, a smartphone or other portable processing device, such as a watch-like device
30 worn at a wristband, or the like. The power meter may be part of a monitoring system comprising the power meter and one or more devices for monitoring

one or more other performance parameters of the bicycle and/or one or more physiological parameters of an athlete using the bicycle, e.g. a heart rate monitor, and/or the like.

- 5 The radiation may be radiation of a suitable wavelength or wavelength range, such as visible light, ultra-violet light, near-infrared light, etc. The radiation source may be a light-emitting diode (LED), a laser, e.g. a vertical cavity surface emitting laser (VCSEL), or a similar radiation source providing a directional radiation beam. The radiation source may be configured to emit a
- 10 light beam within the near-infrared wavelength range, such as between 800 nm and 1000 nm, e.g. between 800 nm and 900 nm, e.g. around 850 nm, or light of another suitable wavelength or range of wavelengths. One advantage of using a near-infrared source is that the quantum efficiency of near-IR sources is typically larger. Another advantage of using a near-infrared source
- 15 is that the detection efficiency of typical silicon-based detectors is larger. The radiation source may be pulsed in order to save energy. One advantage of using a laser is that the divergence of the radiation beam is smaller, which makes it easier to direct all the radiation to the position-sensitive detector. The radiation source may be a diode laser driven below threshold. In this
- 20 case the laser works effectively as an incoherent light source, which may be beneficial in terms of avoiding speckle formation and other interference effects in the light. Another advantage of driving the laser below threshold is lower energy consumption.
- 25 The one or more optical elements for redirecting the radiation beam may be one or more reflective elements, optionally including one or more internally reflecting elements, such as a mirror or a prism. The one or more optical elements may comprise a first optical element configured to redirect the emitted radiation beam along the longitudinal direction; and a second optical
- 30 element configured to redirect the redirected beam towards the position-sensitive detector. In some embodiments, the first and second optical

elements are spaced apart in the longitudinal direction and configured to cause the redirected beam to travel across a surface of the support member. In some embodiments the one or more optical elements are formed as a single element comprising a first redirecting part configured to redirect the emitted radiation beam along the longitudinal direction through at least a portion of the single element; and a second redirecting part configured to redirect the redirected beam towards the position-sensitive detector.

The sensor may comprise one or more additional optical elements such as one or more lenses, filters, reflective elements, etc. for shaping, focusing, collimating, redirecting, filtering and/or otherwise modifying the radiation beam. In particular, an aperture could be placed adjacent to an optional collimating lens or close to the light source in order to reduce the influence of any beam wandering from the light source.

The position-sensitive radiation detector may be any detector adapted to generate a sensor signal responsive to a change in position of the radiation beam relative to a detection position defined by the position-sensitive detector. The terms "position of the radiation beam" and "movement of the radiation beam across the detector" are intended to refer to the position of an illuminated spot on the position-sensitive radiation detector illuminated by the radiation beam impinging on the position-sensitive radiation detector, and to the movement of said illuminated spot, respectively. Examples of position-sensitive radiation detectors include a photosensitive element defining an aperture and adapted to generate a sensor signal responsive to a relative portion of a light beam propagating through the aperture and impinging on the photosensitive element. Other examples include a detector defining a detection area and adapted to generate a sensor signal indicative of a beam position within the detection area. For example, such a detector may be implemented as an array of two or more photosensitive elements, each adapted to generate a sensor signal indicative of a light intensity impinging

on said element. For example, the position-sensitive detector of a deformation sensor described herein may be a single photodiode, a bi-cell photodiode comprising two photodiodes positioned close to one another, or an array of more than two photodiodes, e.g. quadrant photodiodes, a linear diode array or a CMOS- or a CCD-array. Bi-cell photodiodes and linear diode arrays may be used to detect one-dimensional deformations, whereas quadrant photodiodes and 2D sensor arrays may be used to detect two-dimensional deformations. In yet another embodiment, the position-sensitive detector may be a CMOS camera configured to perform a peak finding algorithm that tracks the location of the laser spot on the detection area of the camera. Hence, in some embodiments the position-sensitive radiation detector may be adapted to detect movement of the radiation beam across the detector along two dimensions, thus providing a 2D deformation sensor allowing detection of a bending in two dimensions.

The radiation beam at the position-sensitive detector may be sized to give maximum sensitivity in terms of sensor signal versus bending of the sensor. In case the detector is a bi-cell or multi-cell photodiode, the beam size may be selected to be substantially equal to the size of a single cell.

The present invention relates to different aspects including the cycle power meter described above and in the following, and further apparatus, methods, devices, and/or product means, each yielding one or more of the benefits and advantages described in connection with the first mentioned aspect, and each having one or more embodiments corresponding to the embodiments described in connection with the first mentioned aspect and/or disclosed in the appended claims.

In particular, according to one aspect disclosed herein is a crank set of a bicycle comprising a power meter as described herein. The crank arm or another component of the crank set has the power meter attached to it or

comprises the power meter as an integral part. According to another aspect, disclosed herein are embodiments of a bicycle which comprises a power meter as described herein.

- 5 According to one aspect, disclosed herein are embodiments of a deformation sensor for measuring the bending or twisting/torsion of an object caused by an applied torque. Embodiments of the deformation sensor are attachable to a body as a single deformation sensor unit and are configured to detect a deformation of said body in at least one bending plane, the deformation
- 10 sensor comprising:
- a support member attachable to said body, the support member defining a longitudinal direction in said bending plane;
 - a radiation source fixedly attached to the support member, wherein the radiation source is adapted to emit a radiation beam;
 - 15 - a position-sensitive radiation detector fixedly attached to the support member such that the radiation beam moves across the position-sensitive radiation detector when said support member is bent; and wherein the position-sensitive detector is operable to detect said movement.
- 20 It will be appreciated that embodiments of the deformation sensor described herein may be used to measure deformation, in particular bending or twisting/torsion, of an object, in particular an elongated object, and/or to measure the torque that is applied to the object and causes the bending or twisting/torsion. Consequently, the deformation sensor described herein may
- 25 equally well be referred to as torque sensor. When the deformation sensor is arranged to measure a bending, the deformation sensor may also be referred to as a bending sensor. Similarly, when the deformation sensor is arranged to measure torsion, i.e. twisting of an object due to an applied torque, the deformation sensor may be referred to as a torsion sensor.

Embodiments of the deformation sensor are manufactured as a single sensor unit that is easy to install on a body so as to allow monitoring bending or twisting/torsion of the body and/or torque applied to the body. The sensor unit comprises the radiation source, the radiation detector and the optical elements for directing the light beam from the radiation source to the detector, all fixedly mounted relatively to each other on a sufficiently stiff support member. The deformation sensor may be aligned and/or calibrated already during manufacturing of the sensor, thus resulting in a ready-to-use sensor unit. Here aligning refers in particular to an alignment of the radiation source with respect to the position-sensitive radiation detector; calibrating refers to calibration of the sensor so as to cause the generated sensor signal to suitably reflect the quantity to be measured, e.g. the degree of bending or twisting/torsion. This alignment and/or calibration procedure may be performed using automation, robots and the like, and hence, does not require manual handling or trained personnel. After manufacturing of the sensor unit, the aligned and calibrated sensor may easily be mounted at the construction without additional need for alignment or calibration. It will be appreciated that attachment to an object of unknown properties may require calibration with respect to one or more of these properties, when the relationship between the quantity to be measured, e.g. the torque, and the degree of bending or twisting/torsion depends on one or more of these properties. A post-assembly calibration may be performed after mounting, e.g. by hanging a known weight on the object e.g. a crank arm, or by otherwise applying a known torque to the object. One calibration procedure could be to let the cyclist stand on both pedals and thereby applying a known torque known as half the cyclist's weight multiplied by the crank arm length. A recalibration may also be performed after being used for several hours, weeks, or years.

Embodiments of the deformation sensor may be manufactured in a cost-efficient manner. Embodiments of the deformation sensor are compact and may be attached to many different objects without requiring a lot of space.

For example, embodiments of the deformation sensor may be used as part of a bicycle power meter, where the power meter comprises a deformation sensor configured to detect a bending or twisting/torsion of a mechanical part when a force is applied to said mechanical part. The mechanical part may be
5 a crank arm or another component of the crank set, e.g. a crank spider holding the chain ring, a crank axle, or an axle of a pedal mounted to the crank arm. For example, the sensor may be attached to one of the radial arms of the spider that supports the chain ring.

10 For example, a pre-manufactured sensor unit may be mounted into a pre-manufactured groove of a crank arm or other object without having to realign or recalibrate the sensor. Alternatively, the sensor unit may be mounted in an enclosure or support that may be fixed to a crank arm or other object, for example by mechanical means, by gluing or by other means, and the sensor
15 unit may be used interchangeably between different bicycles or other apparatus.

The support member may comprise a flat plate or substrate on which the radiation source and the position-sensitive radiation detector are mounted.

20 For example, the substrate may be between 0.1 mm and 5 mm thick, e.g. between 0.5 mm and 2 mm. In some embodiments, the support member comprises an optical waveguide to which the radiation source and the position-sensitive radiation detector are optically coupled. In alternative embodiments, the support member is a tube. The support member thus
25 provides protection against humidity and dirt while allowing for a compact and flat design. The support member may have a sufficient stiffness to maintain proper alignment of the optical components during transport, mounting and use of the sensor. The support member may be constructed from a single solid and, preferably, sufficiently stiff material such as polymer
30 or metal.

In some embodiments, the support member is sufficiently stiff so as to cause the sensor unit, when held at its one end seen in the longitudinal direction (e.g. at the position of the radiation emitter) with the longitudinal direction being horizontally aligned and with the bending plane being vertically aligned, to bend less than by a bending radius of 200 m, such as less than by a bending radius of 300 m, such as less than by a bending radius of 500 m.

For example, the bending radius R of a beam deflected by a torque Γ is

$$R = \frac{E I}{\Gamma},$$

where E is Young's modulus for the material and I is the moment of inertia.

For a typical aluminum crank arm $E = 70$ GPa and $I = 4 \cdot 10^{-8} \text{ m}^4$. If there is a desire to detect a minimum detectable torque of 1 Nm, the corresponding bending radius is 2.8 km. Therefore, if the sensor is held at one end, one would not wish for it to bend more than corresponding to 10 times the minimum detectable torque. Hence, for a typical crank arm, this corresponds to a minimum allowable bending radius of 280 m.

The support member may be attached to the bending object by a suitable adhesive or putty material. In this manner, the support member may be attached fixedly without deforming the support member and thereby disturbing the alignment of the sensor, because the adhesive or putty may fill out gaps between the support and the bending object.

The support member may also be attached to a preshaped clamp, in which the clamp is fixed to the object. If the clamp is glued to the object, the clamp may define a shape to which the support member may be attached by screws without disturbing the alignment. In this case the sensor may be removed again and transferred to another object without disturbing the alignment.

If the clamp is screwed to the object, the shape of the clamp may be disturbed. In this case the support member may be glued to the clamp in order to fill out the gaps caused by said disturbance. In this case the clamp may be removed from the object without leaving any marks from glue, etc.

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In order to obtain aligned fixation points for mounting the support member, the clamp may be supplied with a stiff template having a shape and size matching the support member or at least the positions of the fixation points to be used for mounting the support member to the clamp. The template is then attached to the clamp via the fixation points, after which the clamp is mounted to the object, while the template keeps the alignment of the fixation points. The template is then removed after which the real support member is attached to the fixation points. Because the fixation points are still aligned, the support member can be attached to the clamp without disturbing the alignment of the sensor.

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The clamp may also be supplied with an adaptor that exactly fills out the gap between the object and the clamp, so that the clamp is minimally deformed during fixation.

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In some embodiments, the position-sensitive radiation detector and/or a radiation reflector is attached to the support member spaced apart from the radiation source so as to define a portion of the support member along which the radiation beam propagates from the radiation source to the position-sensitive radiation detector. At least said portion of the support member may have a substantially uniform stiffness. In some embodiments, the material is selected so as to not significantly alter the mechanical properties of the object to be monitored. To this end, the support member may be manufactured as a uniform element having substantially uniform properties, in particular a substantially uniform thickness and substantially uniform material.

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- In some embodiments, the radiation source and the position-sensitive radiation detector are located proximal to a first end of the optical waveguide, and wherein a second end of the waveguide is adapted to reflect radiation
- 5 from the radiation source back towards the position-sensitive radiation detector. In some embodiments, the second end is formed as a retroreflector or as a mirror, for example a curved mirror configured to focus the radiation from the radiation source onto the position-sensitive radiation detector.
- 10 In some embodiments, the optical waveguide comprises a prism shape or similar redirecting element embedded into the waveguide, wherein the radiation source and the position-sensitive radiation detector are attached to a side face of the waveguide, and wherein the prism shape is adapted to redirect a transverse radiation beam propagating from the side face towards
- 15 a center of the waveguide into a longitudinal radiation beam propagating along a longitudinal direction of the waveguide. Hence, a compact sensor is provided that may be manufactured in a cost-efficient manner.

Brief description of the drawings

- 20 The above and/or additional objects, features and advantages of the present invention, will be further elucidated by the following illustrative and non-limiting detailed description of embodiments of the present invention, with reference to the appended drawings, wherein:
- 25 Fig. 1a shows an example of a bicycle comprising a power meter.
Fig. 1b shows an example of a crank set comprising a deformation sensor.
Fig. 2 shows a deformation sensor.
Fig. 3 shows another deformation sensor.
Fig. 4 shows an example of a crank arm comprising a deformation sensor.

Fig. 5 shows an example of a deformation profile of a typical 175 mm long crank arm, made from aluminum, when a force of 100 N is applied to the pedal.

Fig. 6 shows an example of the light spot displacement versus sensor length
5 for a sensor attached to a crank arm that is bent according to Fig. 5.

Fig. 7 schematically shows an example of a position-sensitive detector for use in a deformation sensor.

Fig. 8 shows an example of a normalized displacement signal as a function of the displacement from the center of the detector.

10 Fig. 9 shows an example of the temporal variation of a torque measurement during two cycles of a crank arm.

Fig. 10 illustrates a dynamic baseline calibration.

Fig. 11 illustrates examples of alternative positions of a deformation sensor on a crank set of a bicycle.

15 Figs. 12-19 show different examples of a deformation sensor.

Fig. 20 schematically illustrates an example of a wind sensor.

Fig. 21 schematically shows an example of a joy stick.

Fig. 22 schematically shows an example of a deformation sensor attached to a rotating shaft of a wind turbine.

20 Fig. 23 schematically shows a deformation sensor attached to a wind blade of a wind turbine.

Figs. 24 - 27 schematically show further examples of a deformation sensor.

Figs. 28 - 29 show examples of a bending sensor holder to mount on a bicycle crank arm.

25 Figure 30 shows amplification of the photocurrent from two photodiodes.

Fig. 31 illustrates an example of a measurement principle when using on-off modulation of the light source.

Fig. 32 shows an example code to extract the light-induced samples from the sampled signal.

Fig. 33 shows an example of a circuit for amplification and sampling of two detector channels individually. The digital processor calculates the ratio and performs linearization to obtain the position of the light spot.

Fig. 34 shows an example of a circuit for amplification and sampling of a sum
5 and a difference signal.

Figs. 35 - 36 show examples of a torque sensor mounted to an axle such as the axle of a crank set or a pedal.

Fig. 37 shows another example of a bending sensor holder to mount on a bicycle crank arm.

10

Detailed description

In the following description, reference is made to the accompanying figures, which show by way of illustration how the invention may be practiced.

15 Fig. 1 shows an example of a bicycle. In particular, fig. 1a shows a schematic view of a bicycle while fig. 1b shows an enlarged, schematic view of parts of the crank set of the bicycle. The crank set comprises a crank arm 104 which comprises an elongated member radially extending from a bottom bracket 106 to a pedal 107. The bottom bracket connects the crank set to the bicycle
20 frame and allows the crank set to rotate freely. It contains a spindle to which the crank set is attached and the bearings that allow the spindle and crank arms to rotate. The bottom bracket fits inside the bottom bracket shell, which connects the seat tube, down tube and chain stays as part of the bicycle frame. One end of the crank arm is connectable to the bottom bracket. The
25 chain ring 105 is held by the spider 108. The spider and the crank arm may be separate components or integrated into a single component. The pedal 107 is attached to the other end of the crank arm.

The bicycle comprises an optical deformation sensor 101 as described herein
30 attached to one of the crank arms 104 of the bicycle. In the example of fig. 1 the optical deformation sensor 101 is attached to the crank arm along with an

electronic sampling-and-transmitting-unit 102. A data-receiver-and-processor 103 is attached to the handle bar of the bicycle. This data-receiver-and-processor calculates the power, based on the measured sensor signal, and displays the result to the athlete via a display. For example, the sampling-and-transmitting-unit 102 may be implemented as suitable circuitry integrated into or communicatively connected to the sensor 101. The sampling-and-transmitting-unit 102 comprises suitable analogue and/or digital circuitry for signal processing, and a radio transmitter or other suitable wireless communications interface for transmitting the acquired signal to the data-receiver-and-processor 103. The electronic sampling-and-transmitter-unit may be electrically powered by a battery or it may be powered, at least partly, by an inductive system, in which a magnet attached to the bicycle frame induces a voltage in an inductive coil attached to the crank arm, which charges either a capacitor or a battery, also attached to the crank arm, which then powers the electronic sampling-and-transmitter-unit.

The data-receiver-and-processor 103 comprises a corresponding radio receiver or other suitable wireless communications interface for receiving the transmitted signal from the sampling-and-transmitting unit 102, and signal and/or data processor for computing the power and/or another suitable parameter from the received signal.

The crank arm may comprise a recess or cavity for accommodating the optical deformation sensor. Alternatively, the deformation sensor may be attached to a conventional crank arm. Generally, the deformation sensor may define a longitudinal axis along which the light beam propagates. The deformation sensor may be attached to a side face of the crank arm with the direction of the light beam substantially aligned with the longitudinal direction of the crank arm on a side face of the crank arm facing the axial direction, i.e. the axis defined by the torque vector.

Fig. 2 shows a schematic view of an example of a deformation sensor, e.g. for use in a bicycle power meter. The deformation sensor comprises a light source 208 and a light detector 209 both attached to a support 212, and adapted to direct a light beam 210 emitted by the light source 208 to hit the
5 detector 209. The detector may define an aperture, and the light beam may be sized to fit the aperture of the detector.

Fig. 2a shows the sensor in a situation where no torque is applied, while fig. 2b shows the sensor when a torque is applied to it caused by a force F
10 applied to the support, as indicated by an arrow.

The force F causes the support 212 to bend as illustrated in Fig. 2b. The bending results in a movement of the detector 209 relative to the light beam 210, resulting in a decrease of the measured light intensity relative to a
15 central alignment of the light beam 210 relative to the detector 209 when no force is applied (as illustrated in fig. 2a), corresponding to a maximum sensor signal. The detector 209 is positioned such that the light beam 210 escapes the detection area or aperture of the detector 209 upon applying a predetermined maximum force to the crank arm, thus causing the detection
20 signal to be reduced to zero. In this way a maximum measurement range will be assured. In this case the relative change in the electrical signal obtained from the sensor is 100% of the maximum signal. The maximum force may be predetermined, for example, by a manufacturer of the power meter based on information about a given rider (or a typical rider) of a bicycle and about a
25 given crank arm.

The light source 208 may be a laser, such as, for example, a VCSEL, or an LED in combination with a lens.

30 Fig. 3 shows another example of a deformation sensor. The sensor of fig. 3 is similar to the sensor of fig. 2 in that it comprises a support 212 having

attached to it a light source 208, e.g. a VCSEL, and a radiation detector 209, all as described in connection with fig. 2. In the example of fig. 3, the deformation sensor comprises a lens 311 focusing the light beam from the light source 208 onto an aperture or active area of the detector 209.

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Fig. 4 shows an example of a deformation sensor. The deformation sensor of fig. 4 is similar to the deformation sensor of fig. 2 in that it comprises a light source 408, e.g. an LED or a laser, and a radiation detector 409, such that the light source directs a light beam 410 onto the detector 409, all as described in connection with fig. 2. In the example of fig. 4, the deformation sensor comprises a support member 412 formed as an elongated member where the light source is located proximal to one end of the elongated support member 412 while the detector is located at the other end of the elongated support member 412 such that the light beam propagates along the elongated support member and, in particular, along the longitudinal axis of the support member. For example, the elongated support member may be formed as a flat plate. The light beam 410 may be directed along one of the surfaces of the plate. Alternatively, the support member may be an optical waveguide and the light beam 410 may propagate through the waveguide. Yet alternatively, the support member may be a tubular member or otherwise define a cavity through which the light beam may propagate. The elongated member 412 is shorter than the crank arm and, in particular, the distance between the light source 408 and the detector 409 is shorter than the distance between the axis defined by the bottom bracket 406 and the axis 413 of the pedal 407. The light beam propagates in the longitudinal direction of the crank arm.

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When the athlete exerts a torque Γ to the crank arm 404 via pedal 407, the crank arm will deform, mainly by bending in a plane perpendicular to the axis of rotation of the crank arm. This deformation causes the light beam 410 to move across the position-sensitive detector 409 accordingly. Hence, the

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position of the light beam on the detector carries information on the deformation of the crank arm and, hence, the torque exerted.

The local deflection δ of the crank arm at the length coordinate x , measured
 5 from the axis of rotation 406 of the crank arm, will mainly follow the following form:

$$\delta(x) = \frac{\Gamma x^2(3-x/L)}{6EI}, \quad (1)$$

where L is the distance from the rotation axis 406 of the crank arm to the
 10 point at which the force is applied (= position 413 of the pedal 407), E is the modulus of elasticity of the crank arm material and I is the moment of inertia of the crank arm.

Fig. 5 shows an example of a deformation profile of a typical 175 mm long
 15 crank arm, made from aluminum, when a force of 100 N is applied to the pedal.

Preferably, the deformation sensor is located close to the axis of rotation of the crank arm because the curvature of the bending profile is usually largest
 20 here and therefore gives rise to a larger movement of the light spot on the detector. For example, in some embodiments, the sensor is positioned such that the point of the beam path of the light beam closest to the axis of rotation of the crank arm is displaced from the axis of rotation of the crank arm less than 100 mm, e.g. less than 70 mm such as less than 50 mm. The point of
 25 the beam path of the light beam closest to the axis of rotation of the crank arm may e.g. be defined by the position of the light source, the position of the detector, or by the position of a reflective element.

Fig. 6 shows an example of the light spot displacement versus sensor length
 30 for a sensor attached to a crank arm according to Fig. 4 that is bent

according to Fig. 5. The sensor is mounted with the light source being 30 mm from the axis of rotation of the crank arm. The length of the sensor is measured as the length of the beam path of the light beam.

- 5 Fig. 7 schematically shows an example of a position-sensitive detector for use in a deformation sensor. As mentioned above, the position-sensitive detector of a deformation sensor described herein may be a single photodiode, a bi-cell photodiode comprising two photodiodes positioned close to one another, an array of more than two photodiodes, or another type
- 10 of position-sensitive detector. An example of a bi-cell photodiode is shown schematically in Fig. 7, generally designated 709. The bi-cell photodiode comprises two cells 714 and 715 that generate photocurrents I_1 and I_2 , respectively. For illustrating purposes, the bi-cells are here assumed illuminated by a light spot with a Gaussian-shaped intensity cross-section
- 15 716. In Fig. 7 the centroid of the light spot is displaced by a distance z from the center position of the bi-cell photodiode 709.

The photocurrents may be processed according to the following normalized difference algorithm to give a normalized displacement signal S :

$$S = \frac{I_1 - I_2}{I_1 + I_2}$$

- 20 The above and/or other data-processing steps may be performed by a suitable signal processing circuit, e.g. a DSP or suitable analogue circuitry comprised in or connected to the deformation sensor, e.g. the sampling-and-transmission circuit 102 or the data-receiver-and-processor circuit 103 of fig. 1.

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For a Gaussian-shaped beam with a 1/e-intensity radius ω_0 which, for the purpose of simplicity of illustration, is assumed equal to the width of one photodiode cell, the signal S assumes the form

$$\frac{I_1 - I_2}{I_1 + I_2} = 1 \frac{2 \left(\operatorname{Erf} \left[1 - \frac{z}{\omega_0} \right] + \operatorname{Erf} \left[\frac{z}{\omega_0} \right] \right)}{\operatorname{Erf} \left[1 - \frac{z}{\omega_0} \right] + \operatorname{Erf} \left[1 + \frac{z}{\omega_0} \right]}, \quad (2)$$

where the error function $\operatorname{Erf}[z]$ is defined as

$$\operatorname{Erf}[z] = \frac{1}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$$

Fig. 8 shows an example of signal S as a function of the displacement z from the center of the detector, where z is measured in units of the cell-width of each cell. The above normalized displacement signal removes the influence of laser intensity fluctuations.

In the example shown in Fig. 8, the $1/e$ Gaussian beam width is equal to the cell-width of one photodiode. If the beam width is reduced, the curve in Fig. 8 gets steeper and, hence, the sensitivity increases. However, this increase in sensitivity occurs at the expense of the measurable displacement range, which decreases. The measurement range may, however, be expanded by using three or more photodiode cells. The width of the light spot at the position-sensitive detector may be increased by placing the detector in front of or behind the focus of the beam.

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Based on the measured signal S , the displacement z of the spot may thus be calculated using eqn. (2). The torque exerted on the crank arm may then be calculated using eqn. (1). Again, these calculations may be performed by a suitable signal processing unit as described above.

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Fig. 9 shows an example of the temporal variation of a torque measurement during two cycles of a crank arm. The largest peak in torque during a cycle is

observed when the crank arm is in a horizontal position moving downwards, as illustrated by crank arm 904-1 schematically shown above the first peak 917 on the left of the diagram. At the vertical, downwards position of the crank arm, the torque is at least approximately vanishing, as illustrated by
 5 crank arm 904-2. During upward motion of the crank arm, the athlete may be pulling the pedal with a moderate torque resulting in a smaller torque peak 918, as illustrated by crank arm 904-3. Finally, in the vertical upwards position of the crank arm, the torque at least approximately vanishes, as illustrated by crank arm 904-4.

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From the measurement of the torque as a function of time, the average pushing power P_{PUSH} and pulling power P_{PULL} are given by:

$$P_{PUSH} = \pi f \bar{\Gamma}_{PUSH},$$

$$P_{PULL} = \pi f \bar{\Gamma}_{PULL},$$

15 where f is the cycling cadence (number of revolutions of the crank arm per second) and $\bar{\Gamma}_{PUSH}$, $\bar{\Gamma}_{PULL}$ are the time-averaged push and pull torque given by

$$\begin{aligned} \bar{\Gamma}_{PUSH} &= \frac{1}{T_1} \int_0^{T_1} \Gamma(t) dt, \\ \bar{\Gamma}_{PULL} &= \frac{1}{T_2} \int_0^{T_2} \Gamma(t) dt, \end{aligned} \quad (3)$$

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where T_1 is the time it takes for the crank arm to rotate from the up to down position, and T_2 is the time it takes for the crank arm to rotate from down to up position, as illustrated in Fig. 9. Usually, $T_1 \approx T_2 \approx 1/(2f)$. It should be noted that in case the athlete rests his foot on the pedal during the pedal's
 25 upwards movement, P_{PULL} will be negative. The total power exerted on one crank arm is given by $P_{PUSH} + P_{PULL}$.

The cadence may be deduced directly from the measured torque data, as illustrated in Fig. 9 [$f=1/(T1+T2)$], or it may be deduced from accelerometers mounted in the electronic unit, or, yet alternatively, it may be supplied from a magnet mounted on the frame of the bicycle, which induces a signal in a coil/Hall sensor/Reed switch/another magnetic sensor, mounted in the electronic unit, when the electronic unit passes the magnet.

After long-term use, a crank arm may deform, resulting in a slight, permanent bend in the push direction, even without activating the crank arm. This creates a constant false torque signal from the sensor. In order to eliminate this false signal, the signal processing circuitry of the sensor or data processing unit may use a dynamic baseline as a new “zero force” line, as illustrated in Fig. 11, where the minima between the push and pull peaks may be used as zero levels in the integrations leading to and $\bar{\Gamma}_{PUSH}$ and $\bar{\Gamma}_{PULL}$ in Eqs. (3).

For example, in a system as illustrated in fig. 1, the normalized displacement signal data S is digitally sampled by the electronic sampling-and-transmitter-unit 102. The sampling-and-transmitter-unit 102 then wirelessly transmits the sampled data to the data-receiver-and-processor 103 which may be positioned at the handle bar of the bicycle. The data-receiver-and-processor 103 uses Eqs. (1) – (3) to compute the push and pull power, which are then displayed to the athlete by the data-receiver-and-processor. The data-receiver-and-processor may calculate and display push and pull power for both right and left leg, respectively, and it may display the cadence and the associated averaged values. Alternatively, the data-receiver-and-processor may be worn by the athlete as a wrist watch. Additionally, relevant information may be transferred to a smart phone or tablet PC during or after the exercise. Alternatively, the power calculation may be performed by the electronic sampling and transmitter unit, which then transmits the calculated power data to the data receiver.

In some embodiments, instead of attaching the deformation sensor to the crank arm, the deformation sensor of a power meter may be attached to or integrated into another component of the crank set of a bicycle. Fig. 9
5 illustrates examples of suitable positions.

In particular, fig. 11a shows a schematic view of parts of the crank set of a bicycle. The crank set is similar to the crank set shown in fig. 1b in that it comprises a crank arm 104 radially extending from a bottom bracket 106 and
10 having a pedal 107 attached to it. In this embodiment, the chain ring 105 is held by a spider disc 930. The spider disc and the crank arm may be separate components or integrated into a single component. Furthermore, in this embodiment, a deformation sensor as described herein is attached to the spider disc and adapted to measure a torsional deformation of the spider
15 disc. When a torque is applied to the spider disc via the crank arm, a torsion is imposed to the spider disc as illustrated by dotted lines in fig. 11a, causing a bending of the deformation sensor 901 which is registered by the deformation sensor and used to determine the power generated when riding the bike, as described herein.

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Fig. 11b shows a schematic view of parts of another example of a crank set of a bicycle, similar to the one shown in fig. 11a, but where the spider is formed as a set of arms 1131. A deformation sensor 1101 is attached to or
25 formed as an integral part of one of the arms and adapted to measure a bending of the arm 1131 in response to a torque applied to the crank arm 104.

Fig. 11c shows a schematic view of parts of another example of a crank set of a bicycle. The crank set is similar to the crank set shown in fig. 11a in that
30 it comprises crank arms 104 and 1132 radially extending from a bottom bracket 1106 and having respective pedals 107 attached to them. The crank

set further comprises a spider 108 supporting a chain ring. In this embodiment, a deformation sensor 1101 as described herein is attached to or formed as an integral part of the bottom bracket 1106 and adapted to measure a torsional deformation of the bottom bracket, when a torque is
5 applied to the bottom bracket via the crank arms.

In the following examples of a torque or deformation sensor for use in a bicycle power meter as described herein or for other applications will be described in more detail with reference to figs. 12-19.

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In particular, as mentioned above, in order to facilitate the alignment and fixing of the optical components of the deformation sensor during fabrication, the deformation sensor may comprise a support member onto or into which the optical components are attached or otherwise integrated or embedded.

15 Preferably, the support is sufficiently stable to maintain proper alignment during handling and installation of the sensor on or in the crank arm or another object.

Figure 12 shows an example of a deformation sensor comprising a flat,
20 preferably stiff, support member 1212, e.g. a plate, which supports a light source 1208 and a position-sensitive detector 1209 as described herein. The light source and/or detector may be attached directly to the flat support member or, as illustrated in fig. 12, to adjustable posts or other mounting elements allowing alignment of the optical components. The light source and
25 the detector may be aligned and fixed during manufacturing and subsequently mounted, e.g. in a groove in a crank arm, using the support plate 1212 as a lid. Preferably, the lid should form a light and waterproof sealing. The light source may be a light emitting diode (LED), a laser or a similar light source providing a directional light beam. The detector may be a
30 position-sensitive device (PSD) comprising bi-cell or quadrant photodiodes, a linear diode array or it may be a CMOS- or a CCD-array. Bi-cell photodiodes

and linear diode arrays are typically used for one-dimensional deformations, whereas quadrant photodiodes and 2D sensor arrays may be used for two-dimensional deformations.

- 5 Figure 13 shows an embodiment of a deformation sensor, in which the support comprises a hollow tube 1312. The light source 1308 is located at one end of the tube so that the light beam 1310 is directed along the axis of the tube towards a position-sensitive detector 1309 located at the opposite end of the tube. An optical lens (not shown) may be arranged in the beam
- 10 path between the light source and the position-sensitive detector in order to reshape or resize the light beam, such as collimate the light beam. The tube may be made of any suitable material, preferably of sufficient stiffness to maintain proper alignment of the optical components during transport, mounting and use of the sensor. To this end the tube may be made of
- 15 uniform material along its entire length. Preferably, the tube is constructed from one, solid and stiff material, such as polymer or metal. Preferably, the tube is not transparent to ambient light. One advantage of this embodiment is that the light source and the detector are protected from dirt, air currents and ambient light. In one embodiment the support 1312 comprises a solid,
- 20 dielectric rod which is capable of transmitting the light from the light source to the detector. The rod may be metal coated to avoid ambient light from entering the rod. One advantage of this embodiment is that the sensor can be made thinner, since a solid rod is stiffer than a hollow tube.
- 25 Preferably, the light beam 1310 is sized so that no part of the light beam hits the inner wall of the tube in order to avoid reflected light interfering with the directly transmitted light from the light source. Such interfering reflections may cause light fringes or light structures in the light spot, which in turn would lead to a noisy signal curve.

Figure 14 shows an embodiment of a deformation sensor, in which the support 1412 comprises a planar optical waveguide to which a light source 1408 and a position-sensitive detector 1409 are attached. The light source 1408 and the detector 1409 are positioned at opposite ends of the waveguide. the waveguide is formed as a plate having a length in a longitudinal direction of a waveguide, a width in a first transverse direction smaller than the length (e.g. by a factor of at least 2, e.g. at least 3, e.g. at least 5), and a thickness in a second transverse direction that is smaller than the width (e.g. by a factor of at least 2, e.g. at least 3, e.g. at least 5). The first transverse direction is in the plane of the drawing in Fig. 14. The light beam is configured to propagate along the longitudinal direction, and the detector is adapted to detect a movement of the light beam along the first transverse direction of the waveguide, i.e. the sensor is adapted to detect a bending in a plane parallel to the plate.

One advantage of this embodiment is that the thickness of the sensor in the second transverse direction can be made very small, which is advantageous when applied to a crank arm, where space in this direction may be limited. The waveguide may be submerged into a surrounding medium that has a refractive index lower than that of the waveguide. Alternatively, the waveguide may be metal coated, which may be advantageous in terms of avoiding ambient light reaching the detector and in terms of avoiding leakage of light due to bonding material used for fixing the waveguide to the structure.

Figure 15 shows another waveguide embodiment of a deformation sensor. The deformation sensor is similar to the deformation sensor of fig. 14 in that it comprises a support member formed as an optical waveguide 1512, and a light source 1508 and a position-sensitive detector 1509 attached to the waveguide. However, in the example of fig. 15, the light source and the detector are positioned at the same end of the waveguide 1512. The sensor further comprises a reflective element 1519 at the opposite end of the

waveguide which reflects light 1510 from the light source 1508 back through the waveguide 1512 towards the detector 1509. The reflector may be formed by the end face of the waveguide 1512 which thus acts as a mirror. To this end the end face 1519 may be coated with a reflective coating. When the
5 waveguide is deformed, the angle and position of the mirror will change, leading to a movement of the reflected light beam 1520 across the position-sensitive detector 1509. The mirror surface may be metalized to increase the reflectivity of the mirror or the mirror surface may be cladded by a dielectric medium with a refractive index that is different from the refractive index of the
10 waveguide. The cladding dielectric medium may be partly absorbing to avoid reflections from the surroundings. One advantage of the embodiment is that the light source and the detector may be mounted on the same substrate or printed circuit board. Another advantage is that the movement of the laser spot at the position-sensitive detector is increased.

15 Figure 16 shows yet another waveguide embodiment of a deformation sensor. The deformation sensor is similar to the deformation sensor of fig. 15 in that it comprises a support member formed as an optical waveguide 1612, and a light source 1608 and a position-sensitive detector 1609 attached to
20 the waveguide. As in fig. 15, the light source and the detector are positioned at the same end of the waveguide 1612, and the sensor further comprises a reflective element 1619 at the opposite end of the waveguide which reflects light 1610 from the light source 1608 back through the waveguide 1612 towards the detector 1609.

25 However, in the example of fig. 16, the reflecting side 1619 of the waveguide 1612 is shaped as a retro-reflector. When the waveguide is deformed, the angle and the position of the retro-reflector will change, leading to a movement of the reflected light beam 1620 across the position-sensitive
30 detector 1609. If the surrounding medium is air the retro-reflector will be fully reflective due to total internal reflection. This is advantageous since no

metallization of the reflector is necessary. The retro-reflector may also be metalized in order to isolate the waveguide from a surrounding dielectrical material, such as glue, etc.

- 5 Figure 17 shows yet another waveguide embodiment of a deformation sensor. The deformation sensor is similar to the deformation sensor of fig. 15 in that it comprises a support member formed as an optical waveguide 1712, and a light source 1708 and a position-sensitive detector 1709 attached to the waveguide. As in fig. 15, the light source and the detector are positioned
10 at the same end of the waveguide 1712, and the sensor further comprises a reflective element 1719 at the opposite end of the waveguide which reflects light 1710 from the light source 1708 back through the waveguide 1712 towards the detector 1709.
- 15 However, in the example of fig. 17, the reflecting side 1719 of the waveguide 1712 is shaped as a curved mirror. In this case, the light from the light source 1708 may be diverging, hence the light source may be a laser diode such as a Vertical-Cavity-Surface-Emitting-Laser (VCSEL). The profile of the curved mirror may be part of an ellipsoid with the focal points positioned at or near
20 the location of the light source and the detector, respectively. One advantage of the embodiment of fig. 17 is that light from the light source does not have to be collimated to form a small spot at the detector, i.e. no collimation optic is needed. Another advantage is that positioning the beam shaping element (the mirror) far from the light source makes the sensor less sensitive to
25 positioning of the laser and the detector, as compared with the case of a usual collimation lens placed close to the light source.

Figure 18 shows yet another waveguide embodiment of a deformation sensor. In particular, fig. 18a shows a top view of the sensor, while figs 18b-c
30 show respective cross-sectional views through respective, parallel planes along the longitudinal direction of the waveguide and through the position of

the light source and the detector, respectively. The deformation sensor is similar to the deformation sensor of fig. 17 in that it comprises a support member formed as an optical waveguide 1812, and a light source 1808 and a position-sensitive detector 1809 attached to the waveguide. As in fig. 17, the light source and the detector are positioned at, or at least proximal to, the same end of the waveguide 1812, and the sensor further comprises a reflective element 1819 at the opposite end of the waveguide which reflects light 1810 from the light source 1808 back through the waveguide 1812 towards the detector 1809. As in the example of fig. 17, the reflecting side 1819 of the waveguide 1812 is shaped as a curved mirror.

However, in the example of fig. 18, the deformation sensor further comprises a prism-shaped element 1821 that is molded into the waveguide structure. In this case, the light source 1808 and the detector 1809 are placed on top of the waveguide, i.e. on one of the lateral side faces, as shown in Fig. 18. The light source emits a light beam in the transverse direction of the waveguide towards the prism-shaped element 1821. The prism 1821 redirects the light, e.g. by total internal reflection, so that the light 1810 propagates longitudinally in the plane of the waveguide towards the mirror, as illustrated in Fig. 18b. After being reflected off the mirror 1819 the reflected light 1820 is redirected again by the prism 1821 to hit the detector 1809, see Fig. 18c. One advantage of this embodiment is that the light source and the detector are easier to attach to the larger top surface of the waveguide, as compared with an attachment at the smaller end surface. Another advantage is that the substrate on which the light source and the detector are mounted will be oriented along the waveguide, making the assembly more compact. For example, the light source, the detector and signal processing circuitry may be attached to a substrate, e.g. a circuit board, so as to form an integrated unit comprising all electronic components of the sensor. The integrated unit may then be attached to a top face of the waveguide.

Figure 19 shows yet another waveguide embodiment of a deformation sensor. In particular, fig. 19a shows a top view of the sensor, while figs 19b-c show respective cross-sectional views. The deformation sensor is similar to the deformation sensor of fig. 18 in that it comprises a support member

5 formed as an optical waveguide 1912, and a light source 1908 and a position-sensitive detector 1909 attached to the waveguide, all as described with reference to fig. 18. As in fig. 18, the light source and the detector are positioned at, or at least proximal to, the same end of the waveguide 1912, and the sensor further comprises a reflective element 1919 at the opposite

10 end of the waveguide which reflects light 1910 from the light source 1908 back through the waveguide 1912 towards the detector 1909. As in the example of fig. 18, the reflecting side 1919 of the waveguide 1912 is shaped as a curved mirror; in particular, the curved end face is coated with a reflective metal coating. The deformation sensor further comprises a prism-

15 shaped element 1921 that is molded into the waveguide structure. The light source 1908 and the detector 1909 are placed on top of the waveguide, i.e. on one of the lateral side faces, as shown in Fig. 19c. The light source emits a light beam in the transverse direction of the waveguide towards the prism-shaped element 1921. The prism 1921 redirects the light, e.g. by total

20 internal reflection, so that the light 1910 propagates longitudinally in the plane of the waveguide towards the mirror. After being reflected off the mirror 1919 the reflected light is redirected again by the prism 1921 to hit the detector 1909 in a position 1928.

25 The waveguide 1912 is preferably plastic injection molded in e.g. acrylic, ULTEM or another optical plastic. The plastic may be an elastomer such as PDMS or it may be a cured polymer resin, such as a UV curable polymer. The light source 1908 is a VCSEL laser that is glued to a window molded into the waveguide. The light from the laser is then reflected by the prism shape

30 1921 that is also molded into the waveguide. The prism redirects the light towards a curved side 1919 of the waveguide. In the embodiment shown in

Fig. 19, the radius of curvature is 60 mm, while the length of the entire sensor is 75 mm; the focal plane of the concave mirror is indicated by line 1925. The circles 1924 indicate the positions of ejector pins in the mold. The expanded light beam 1923 is reflected and re-focused by the curved mirror 1919 and
5 directed back towards the prism. Here, the light is reflected and redirected by the prism 1921, coupled out of the window to hit the position-sensitive detector 1908 that is also glued to the waveguide. The laser and the detector do not necessarily need to be glued to the waveguide, however, it is preferential in order to avoid or reduce reflections at the waveguide window
10 and reflections at the surfaces of the VCSEL and the position-sensitive detector.

A bending as described in connection with figs. 5 and 6 would for the sensor of fig. 19 result in a displacement of the focused laser spot at the position-
15 sensitive detector by 16 μm . The increased spot deflection of 16 μm , as compared with the waveguide's deflection of only 9 μm (according to Fig. 6) is a result of the reflective geometry.

Embodiments of the invention disclosed herein have mainly been disclosed
20 in the context of a power meter for a bicycle. For example, the power meter may be used on sports bikes, such as racing bikes and mountain bikes, and they may be used on fitness bikes, exercise bikes, spinning bikes, fitness machines and the like. Hence, embodiments of the various aspects described herein may be used in the areas of sport, wellness and home
25 health (such as sports cycles, fitness equipment, physical therapy equipment, etc.).

It will be appreciated, however, that embodiments of the deformation sensor described herein may also be used on any other mechanical construction
30 that is subject to deformation and, in particular, bending or twisting/torsion. Examples of possible applications include:

- Bridges, with respect to monitoring local deformations on structural parts of the bridge
- Automobiles, with respect to monitoring local deformations on structural parts of the vehicle. The deformation sensor may, in addition, be used as part of a feedback system in automatic brakes, automatic shock absorbers, active chassis, etc.
- Ships, with respect to monitoring local deformations on structural parts of the ship, such as masts and steering gear
- Buildings, with respect to monitoring local deformations on structural parts of the building.

For example, an optical wind sensor may comprise a pole and a deformation sensor including a radiation source and a position-sensitive radiation detector, as disclosed herein, in which a radiation beam moves across said position-sensitive detector when a wind force is applied to said pole. Fig. 20 schematically illustrates an example of a wind sensor in which a deformation sensor 2001 (e.g. as described in connection with any one of figs. 12-19) attached to the pole 2004 of an ordinary wind indicator, typically installed at traffic bridges. Via the wind bag 2029 attached to the top of the pole, a force is exerted on the tip of the pole, which causes the pole to bend accordingly. The deformation sensor attached to the pole may be a 2D type, employing, for example, a quadrant photodiode which gives two-dimensional bending data for the pole. Hence, the sensor provides both direction and strength of the wind. In case the pole is sufficiently flexible, a wind bag may not be necessary.

An optical joy stick may comprise a handle bar and a deformation sensor including a radiation source and a position-sensitive radiation detector, in which a radiation beam moves across said position-sensitive radiation detector when a force is applied to said handle bar.

Fig. 21 schematically shows an example of a joy stick, in which a 2D deformation sensor 2101 (e.g. as described in connection with any one of figs. 12-19) is attached to an elastically bendable handle bar 2104 of the joy stick. In this manner 2D information of the force exerted on the handle bar
5 can be detected and used as control signal. The joy stick may be used on wheel chairs, gaming joy sticks for computers, robots, and the like.

An optical torsion sensor for measuring torsional forces on a rotating shaft may comprise a support, a radiation source, and a position-sensitive
10 radiation detector, in which the sensor is attached to the shaft, and in which a radiation beam moves across said position-sensitive radiation detector when a torsional force is applied to said shaft.

Fig. 22 schematically shows an example of a deformation sensor 2201 (e.g. as described in connection with any one of figs. 12-19) attached to a rotating
15 shaft 2204 of a wind turbine. During normal operation the shaft experiences a torque induced by the forces acting on the blades of the wind turbine. The torque induces torsional forces F on the shaft, which in turn causes a twist of the shaft. A 1D deformation sensor will be able to monitor such twists and
20 thereby provide information of the torsional load.

An optical deformation sensor for measuring deformation of a wind turbine blade may comprise a support, a radiation source, and a position-sensitive radiation detector, in which the sensor is attached to the wind turbine blade,
25 and in which a radiation beam moves across said position-sensitive radiation detector when a wind force is applied to the wind turbine blade. Fig. 23 schematically shows a deformation sensor 2301 (e.g. as described in connection with any one of figs. 12-19) attached to wind blades 2304 of a wind turbine. Information regarding the deformation may be used as part of a
30 safety system, i.e. to trigger braking.

Preferably, the sensors in Figs. 22 and 23 are battery driven and communicate wirelessly with a separate monitor unit.

Fig. 24 shows an embodiment of a bending sensor in which a laser 2408 is
5 mounted at one end of a printed circuit board (PCB) 2412 and a detector
2409 is mounted at another end. The distance between laser and detector
may be 10 - 100 mm, but may be smaller or larger. A laser prism 2451 is
mounted on top of the laser. This prism redirects the laser light beam and a
lens shape 2452 molded into the prism makes the light beam 2410 converge
10 towards the detector prism 2453. The detector prism redirects the light beam
towards the position sensitive detector (PSD) 2409, facilitating simultaneous
measurement of bending in two orthogonal directions. One advantage of this
embodiment is that laser and detector may be mounted on the same PCB.
Another advantage is that the critical position between laser and beam
15 shaping unit (here the lens shape) may be fixed by gluing the laser prism to
the PCB.

Yet another embodiment of a bending sensor is shown in Fig. 25. This
embodiment is identical to the one shown in Fig. 24 apart from a U-shaped,
20 hollow (i.e. air-filled) tunnel 2554 that connects the two prisms 2451 and
2453. The two prisms and the tunnel may be molded in one piece. The
advantage of this embodiment is that it is simpler to mount just one prism
instead of two, as the distance between the prism ends are now fixed.

25 In Fig. 26 another embodiment of a bending sensor is shown. In this
embodiment, all the light redirecting/reshaping members 2651 and 2653 are
molded into one prism 2655. There is no air-filled tunnel as in Fig. 25. Instead
the prism 2655 is a solid component. The light shaping at the laser end of the
sensor is performed by a curved reflecting surface 2651, as shown. An
30 advantage of this embodiment is that the prism is easier to manufacture
compared with the prism shown in Fig. 25. Furthermore, the prism may be

glued to the PCB meaning that there will be no air gaps in the light beam and therefore no reflections.

5 In Fig. 27 is shown another embodiment of a bending sensor, similar to the embodiment of Fig. 26, but where the PCB 2712 has the same size as the prism 2655. In this manner the whole sensor package is easier to fit into a holder. The PCB may also be sized to fit into a groove molded into the bottom of the prism 2655.

10 Fig. 28 shows an embodiment of a bending sensor holder 2856 to mount on a bicycle crank arm 2804. For example, the holder may be a ring clamp or sleeve. The bending sensor 2801 is incorporated in the holder in a way so that the bending sensor follows the bending of the crank arm during load. One advantage of this holder is that it is flexible and therefore may fit onto
15 several crank arms.

The bending sensor mentioned in Figs. 24-28 may be a separate unit that includes only the light source and the detector and maybe some basic analogue components such as amplifiers. The further signal processing may
20 be performed in a separate electronics unit 2902, as shown in Fig. 29. This electronics unit may include an AD converter, CPU unit, power supply, such as a battery, and/or a radio transmitter that transmits the bending or power data to a monitor. One advantage of separating the basic bending sensor from the remaining electronic processing is that the basic sensor is then
25 smaller and easier to fit reliably to a crank arm, i.e. making sure that the sensor follows reliably the bending of the crank arm. The mounting of the electronics is not critical in the same way. The basic sensor may be connected to the electronics unit by a flexible cable 2957 as schematically shown in Fig. 29.

All bending sensors mentioned above may be used as bicycle power meters, in which the bending information is converted into torque and the torque is multiplied with the angular frequency to give the power.

5 Photodetection

The position-sensitive detector may comprise two or more photodiodes, but other light detectors such as photo conductive elements could be employed. Figure 30 shows typical setups suitable for amplifying the photocurrent.

- 10 Figure 30 shows examples of circuits for amplification of the photocurrent from two photodiodes D1 and D2. The example of Fig. 30 a) shows a circuit comprising a voltage amplifier A_v which has a high input impedance. The example of Fig. 30 b) shows a circuit comprising a a trans-impedance amplifier A_r which presents a low impedance to the photo detector. V_{bias} is a
15 fixed voltage. After amplification the signal can be converted to digital format by an analogue to digital converter (ADC).

Leakage current mitigation

It is generally desirable to provide a sensor having low power consumption.

- 20 Therefore it is desirable to operate the sensor with low light level. This in turn requires sensitive detectors and low-noise amplification. To maximize detector speed and minimize the capacitance it is beneficial to apply a reverse bias ($V_{bias} > 0$ Volt in Figure 30) voltage over the photodiode. This however gives rise to leakage current in the detector – this current will vary
25 with temperature and fabrication quality. If not compensated for, leakage current will set a lower limit on the detectable light level if it becomes comparable or even larger than the signal itself.

Leakage current compensation by modulation

- 30 However, because this error signal is independent of the light-induced signal one can compensate its effect by measuring the detector current with and

without light exposure. The difference between the two measures is the contribution from the light alone provided the measurement is done over a time span, where there is no significant change in the leakage current. One challenge in such a system is that the amplification chain should encompass
5 the dynamic range of both the light signal contribution, but also the leakage current's contribution. In high sensitivity system the latter can be comparable or exceed the signal contribution.

In such a measurement system, the change of light amplitude or modulation
10 can be an on-off switching sequence, but it is not restricted to this. It can be any kind of amplitude change i.e. between any two or more signal levels, such as a sine wave amplitude modulation. Because both the light source and the detection process are controlled by the instrument, it is possible to make measurements at the precise instances relative to the modulation. This
15 measurement principle when using on-off modulation of the light source is illustrated in Figure 31. An example of an algorithm used to extract the samples from such a sequence is shown in Figure 32.

Figure 31 is an illustration of leakage current compensation using on-off
20 modulation of the light source. The thick, solid curve 3158 is the time evolution of the detector signal when the light source is off (samples 1, 2, 5, 6, 9, 10, and 13). When the light source is on, the signal follows the thin, solid curve sampled at points 0, 3, 4, 7, 8, 11, and 12. The dashed portions 3160 of the thick curve illustrate the hypothetical evolution had the light remained
25 off. The light source is switched on and off at regular intervals. The signal is sampled at the instants indicated by circles and labelled with numbers. If the samples are all taken at a time close to the instant where the light source changes, then the differences between the signal amplitudes (0)-(1) is a good measure of the light-induced signal at the time near (0) and (1). The same
30 applies for the sample pairs (2)-(3) and so forth. For illustration purpose the

light induced signal in Fig. 31 is smaller at samples (6, 7) and (8, 9) than at (4, 5) and at (10, 11).

Figure 32 shows an example code to extract the Light-induced samples $L[j]$ from the sampled signal $S[j]$ in Figure 31. The code is written in the C programming language.

An added benefit of the modulation scheme is that it also compensates for slowly varying amplifier offsets in the amplification chain.

10

Leakage current removal by zero bias.

An alternative method of removing the leakage current contribution is by setting the reverse bias voltage to zero. This will remove the leakage current entirely. Zero bias can be achieved by applying an amplifier with a low input resistance such as the trans-impedance amplifier configuration shown in Figure 30 b) with $V_{bias}=0$ volt. This mode of operation has the advantage that there is no need to repeatedly change the light illumination amplitude (modulation of light level) and the dynamic range endured by the signal amplification and acquisition chain is minimized. The disadvantage is that a photodiode with zero or low bias voltage will have a larger capacitance than compared to the capacitance with reverse bias applied. This gives a slower response time and gives rise to increased high-frequency noise in the amplifier attached to the photo detector. In order to compensate for offset errors in the signal chain, one can employ a modulation scheme similar to what was described in the previous section.

25

Detection of the spot location

A measure of the spot location X along an axis can be computed from the detector signals $S1$ and $S2$ of two photodiodes or other detectors that are positioned adjacent along said axis, e.g. as

30

$$X=(S1-S2)/(S1+S2) \quad (1)$$

Amplification and acquisition of the dual detector signals.

The difference signal (S1-S2) conveys the majority of the position information
5 whereas the sum signal (S1+S2), which is used for normalization, is
constant, provided the light illumination of the two detectors is not varying.
This is the case when the light emitted from the light source is constant and
when the light-spot is not outside of the detectors active area and lastly, the
detectors have uniform sensitivity.

10

At least two approaches can be taken to amplify, acquire and calculate the
position using the detector signals S1, S2 and eqn. (1):

1) Amplify and then acquire each signal S1 and S2 individually and
15 subsequently calculate the difference (S1-S2) and sum (S1+S2) and finally
calculate the ratio according to eqn. (1). A circuit implementing this scheme is
illustrated in Figure 33.

2) Amplify and then acquire the sum signal (S1+S2) and the difference signal
20 (S1-S2) separately. Then calculate the ratio of those two signals according to
eqn. (1). A circuit implementing this scheme is illustrated in Figure 34.

The end result will be similar. The sum signal is larger than the difference
signal, thus the amplification of the difference signal must be larger than the
25 sum signal, to match a similar acquisition channel. This is especially the case
when the light spot only moves a small fraction of the full range away from
the center which would typically be the case when good linearity in position
resolution is needed. In that case the second method is advantageous. In
Figure 33 and Figure 34, a part of the processing is for convenience done
30 digitally, but it can also be done using analogue adder, subtractor and divider
blocks.

Both amplification and acquisition schemes 1 and 2 can be applied for any of the photodiode biasing schemes described. When using the light source modulation scheme, it is the signal after removal of leakage current offset
5 which must be used in the calculation of the sum, difference and ratio.

Figure 33 shows amplification and sampling of each detector channel individually. The digital processor calculates the ratio and performs linearization to obtain the position of the light spot.
10

Figure 34 shows amplification and sampling of sum and difference signal. Each with a gain A_+ and A_- such that the amplitude matches the ADC range. The digital processor calculates the ratio and performs linearization to obtain the position of the light spot.
15

Figs. 35 - 36 show examples of a bending sensor mounted to an axle such as the axle of a crank set or a pedal.

In the example of Fig. 35, a deformation sensor unit 3501 is mounted on the
20 interior surface of a tubular axle 3506 such as the axle of the bottom bracket by which the crank set is connected to the frame of a bicycle, or the axle of a pedal connected to the crank arm. The deformation sensor 3501 is fixedly attached to the interior surface of a support tube 3556 having an outer diameter such that the support tube fits into the void of the tubular axle 3506.
25 The support tube is held in place inside the axle 3606 by an expansion bolt 3562 which engages the support tube via two frusto-conical members 3564 at either end of the support tube. The deformation sensor 3501 may be a sensor unit comprising a support member, radiation source and position-sensitive detector as described herein. Alternatively, the support tube 3556
30 may function as support member, and the radiation source and position-sensitive detector and optionally further components of the deformation

sensor may be attached directly to the support tube. The support tube may thus be made of sufficiently stiff material as described herein, so that an untrained user can easily install it into an existing bottom bracket axle without aligning.

5

In the example of Fig. 36, a deformation sensor unit 3601 is mounted on the exterior surface of an axle 3606. The deformation sensor 3601 is fixedly attached to the exterior surface of a support tube 3656 having an inner diameter such that the support tube fits around the axle 3606. The support
10 tube is held in place by fixation screws 3662 or another suitable attachment means. The deformation sensor 3501 may be a sensor unit comprising a support member, radiation source and position-sensitive detector as described herein. Alternatively, the support tube 3556 may function as support member, and the radiation source and position-sensitive detector
15 and optionally further components of the deformation sensor may be attached directly to the support tube. The support tube may thus be made of sufficiently stiff material as described herein, so that an untrained user can easily install it without aligning.

20 Fig. 37 shows another example of a bending sensor holder 3756 to mount on a bicycle crank arm 3704. For example, the holder may be a ring clamp or sleeve, e.g. as described in connection with Fig. 28. The holder may be mounted first, which may cause a deformation of the holder. After this the sensor is glued onto the holder without being deformed.

25

Although some embodiments have been described and shown in detail, the invention is not restricted to them, but may also be embodied in other ways within the scope of the subject matter defined in the following claims. In particular, it is to be understood that other embodiments may be utilized, and
30 that structural and functional modifications may be made without departing from the scope of the present invention.

In particular, in one general aspect, disclosed herein are embodiments of a bicycle power meter for measuring power generated when riding a bicycle, the power meter comprising a position-sensitive radiation detector fixedly
5 attachable to a support member, and a radiation source fixedly attachable to the support member, in which the support member is fixedly attached to a crank arm and configured to direct a radiation beam towards the position-sensitive detector such that the radiation beam moves across the position-sensitive radiation detector when the component of the crank set bends or
10 twists responsive to torque applied to the component of the crank set.

According to another general aspect, disclosed herein are embodiments of a deformation sensor for measuring the bending or twisting/torsion of an object caused by an applied torque. Embodiments of the deformation sensor
15 comprise a support member, and a radiation source and a position-sensitive radiation detector, each fixedly attached to the support member, wherein the radiation source is adapted to direct a radiation beam towards the position-sensitive detector such that the radiation beam moves across the position-sensitive radiation detector when said support member is bent or twisted.

20

The above general aspects yield one or more of the benefits and advantages described in connection with the aspects described in the introductory portion of this description, and they each have one or more embodiments corresponding to the embodiments described in connection with the aspects
25 described earlier in the present description and/or disclosed in the appended claims.

In device claims enumerating several means, several of these means can be embodied by one and the same item of hardware. The mere fact that certain
30 measures are recited in mutually different dependent claims or described in

different embodiments does not indicate that a combination of these measures cannot be used to advantage.

- 5 It should be emphasized that the term "comprises/comprising" when used in this specification is taken to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other features, integers, steps, components or groups thereof.

Claims:

1. A bicycle power meter for measuring power generated when riding a bicycle, the power meter comprising a deformation sensor for measuring
5 bending or twisting of a component of a crank set of a bicycle responsive to a torque applied to said component, wherein the deformation sensor is attachable to said component as a deformation sensor unit and is configured to detect a deformation of said component in at least one bending plane, the deformation sensor comprising:
- 10 - a support member attachable to said component, the support member defining a longitudinal direction in said bending plane;
- a radiation source fixedly attached to the support member, wherein the radiation source is adapted to emit a radiation beam; and
- a position-sensitive radiation detector fixedly attached to the support
15 member such that the radiation beam moves across the position-sensitive radiation detector when said support member is bent; and wherein the position-sensitive detector is operable to detect said movement.
2. A bicycle power meter according to claim 1, wherein the radiation source is
20 adapted to emit the radiation beam along a direction transverse to said longitudinal direction and the deformation sensor unit comprises one or more optical elements fixedly attached to the support member and configured to redirect the emitted radiation beam along the longitudinal direction and onto the position-sensitive radiation detector.
- 25
3. A bicycle power meter according to claim 2, wherein the position-sensitive detector is adapted to receive a radiation beam from a direction transverse to said longitudinal direction; and wherein the one or more optical elements are configured to redirect the emitted radiation beam along the longitudinal
30 direction and to redirect the redirected beam towards the position-sensitive

detector; wherein the redirected beam travels along the longitudinal direction along a predetermined distance.

4. A bicycle power meter according to claim 3, wherein the one or more
5 optical elements comprises a first optical element configured to redirect the emitted radiation beam along the longitudinal direction; and a second optical element configured to redirect the redirected beam towards the position-sensitive detector.
- 10 5. A bicycle power meter according to claim 4, wherein the first and second optical elements are spaced apart in the longitudinal direction and configured to cause the redirected beam to travel across a surface of the support member.
- 15 6. A bicycle power meter according to claim 3, wherein the one or more optical elements are formed as a single element comprising a first redirecting part configured to redirect the emitted radiation beam along the longitudinal direction through at least a portion of the single element; and a second redirecting part configured to redirect the redirected beam towards the
20 position-sensitive detector.
7. A bicycle power meter according to any one of the preceding claims, wherein the support member comprises an optical waveguide optically coupled to the radiation source and to the position-sensitive radiation
25 detector and adapted to receive the radiation beam emitted by the radiation source and to guide the radiation beam towards the position-sensitive radiation detector.
8. A bicycle power meter according to claim 7, wherein the radiation source
30 and the position-sensitive radiation detector are located proximal to a first end of the waveguide, and wherein the deformation sensor comprises a

reflective element proximal to the second end of the waveguide and adapted to reflect radiation from the radiation source back towards the position-sensitive radiation detector.

5 9. A bicycle power meter according to claim 8, wherein the reflective element is a curved mirror defining a focus point proximal at the radiation source.

10. A bicycle power meter according to any one of claims 7 through 9, wherein the waveguide comprises one or more redirecting element
10 embedded into the waveguide, wherein the radiation source and the position-sensitive radiation detector are attached to a side face of the waveguide, and wherein the one or more redirecting element is adapted to redirect a transverse radiation beam propagating from the side face to a center of the waveguide into a longitudinal radiation beam propagating along a longitudinal
15 direction of the waveguide.

11. A bicycle power meter according to any one of claims 7 through 10, wherein the deformation sensor is configured to detect a bending of said component in said bending plane defined by the support member, wherein
20 the support member has a length and a width defined in the bending plane, the width being smaller than the length, and wherein the support member has a thickness defined in a lateral direction normal to the bending plane, the thickness being smaller than the width.

25 12. A bicycle power meter according to any one of the preceding claims, comprising two deformation sensors attachable to respective crank arms of a crank set.

13. A bicycle power meter according to any one of the preceding claims,
30 further comprising a signal processing unit configured to receive a sensor signal from the position-sensitive radiation detector, wherein the signal

processing unit comprises a communications interface for wireless communicating a measurement signal derived from the sensor signal.

14. A bicycle power meter according to any one of the preceding claims,
5 comprising a processing unit configured to receive a sensor signal from the position-sensitive radiation detector, and to compute a power generated by an athlete from the received sensor signal.

15. A bicycle power meter according to claim 14, wherein computing
10 comprises determining, from the received sensor signal, a baseline amount of bending and computing the power from variations of the amount of bending relative to the determined baseline amount.

16. A crank set for a bicycle comprising a bicycle power meter as defined in
15 any one of claims 1 through 15.

1/14

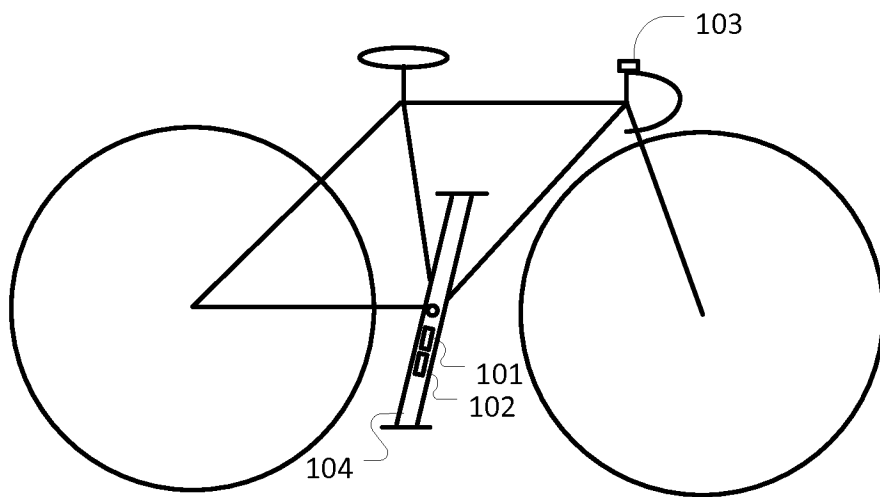


Fig. 1a

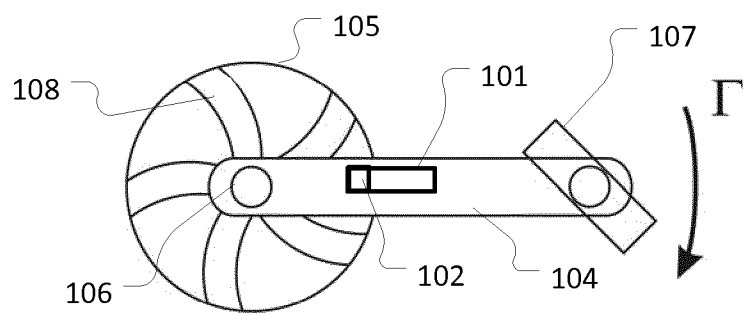


Fig. 1b

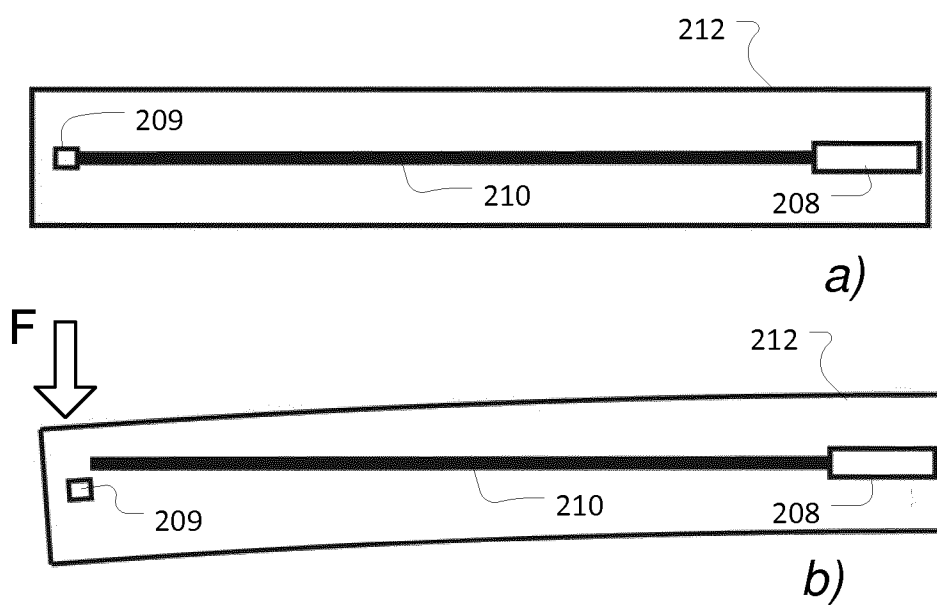


Fig. 2

2/14

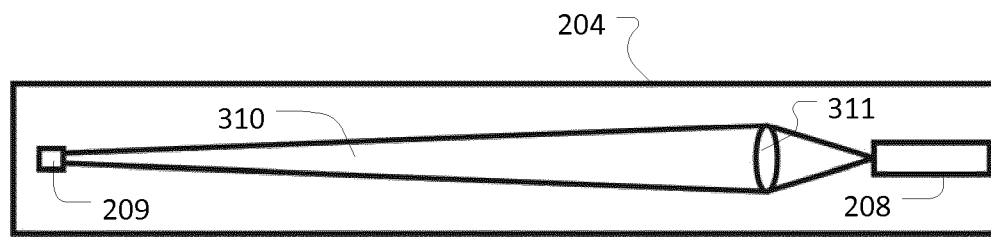


Fig. 3

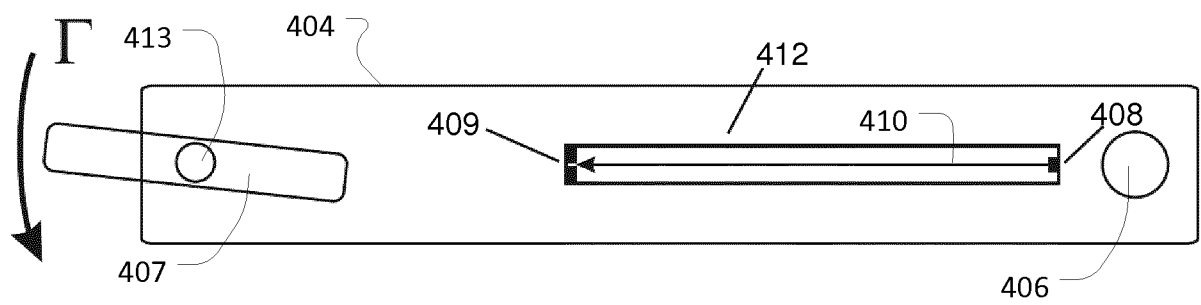


Fig. 4

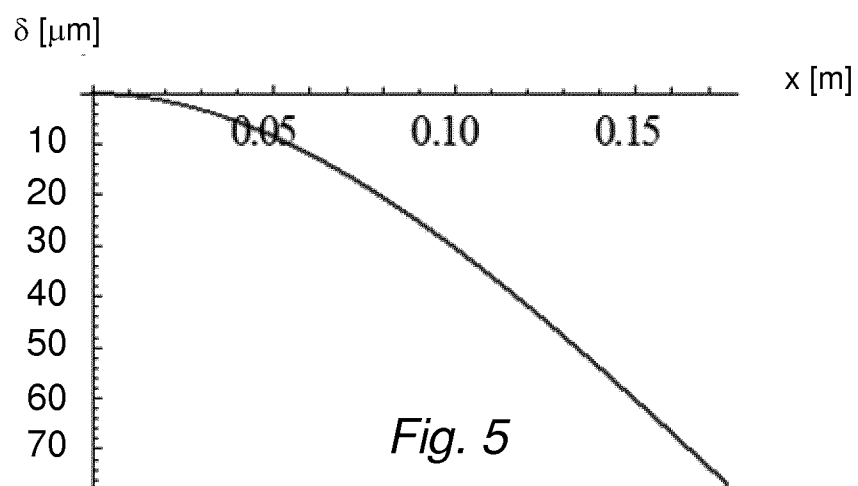


Fig. 5

3/14

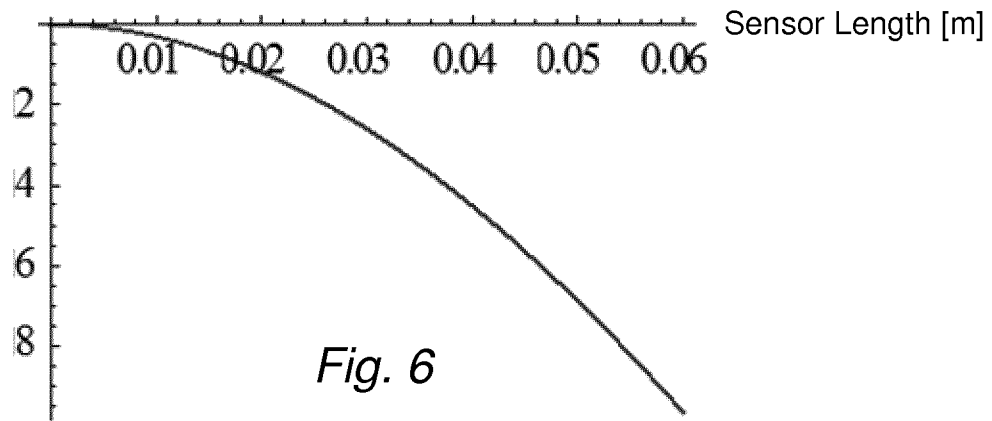
Spot Displacement [μm]

Fig. 6

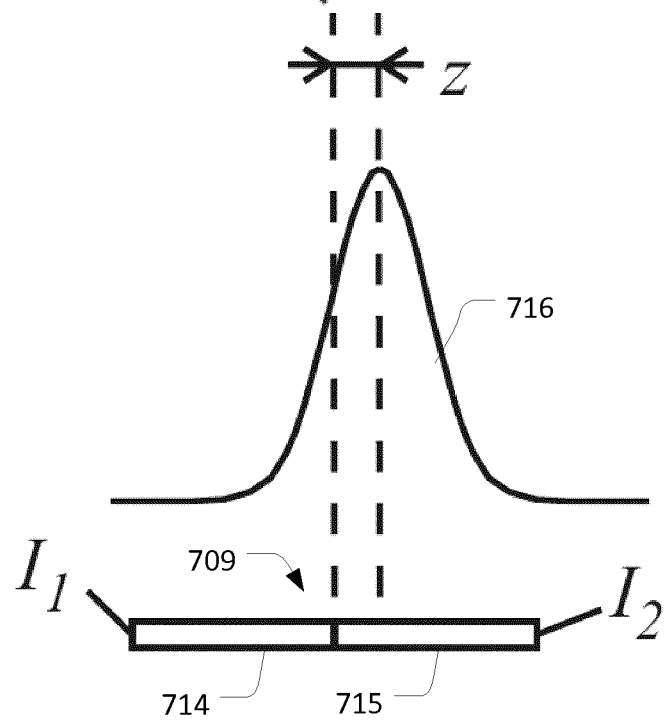


Fig. 7

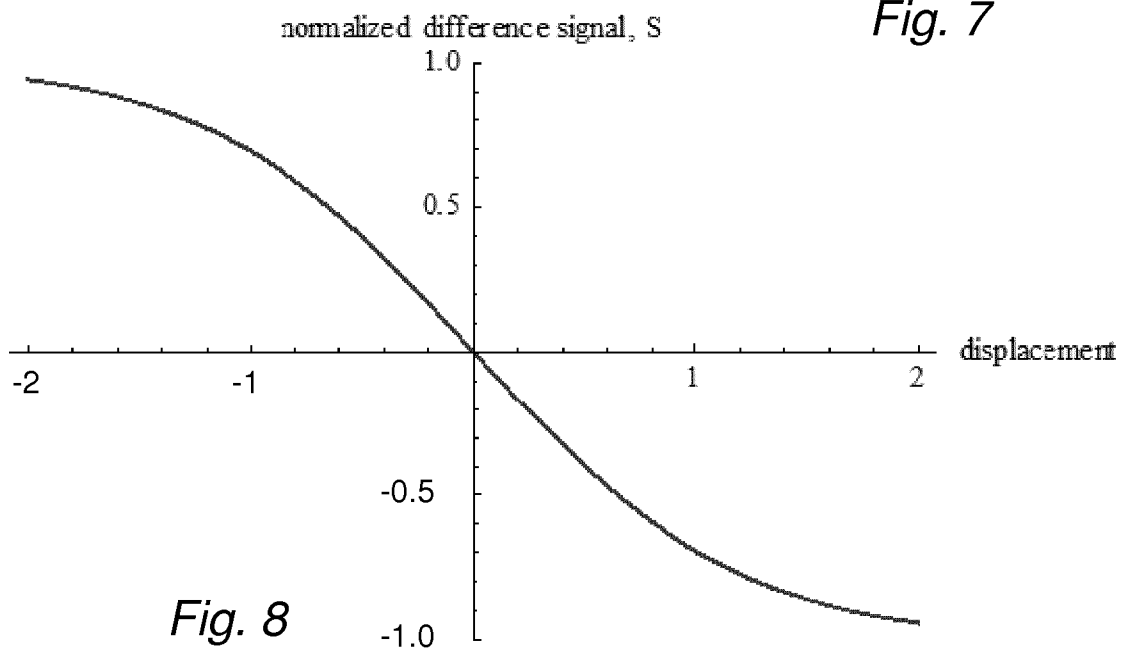
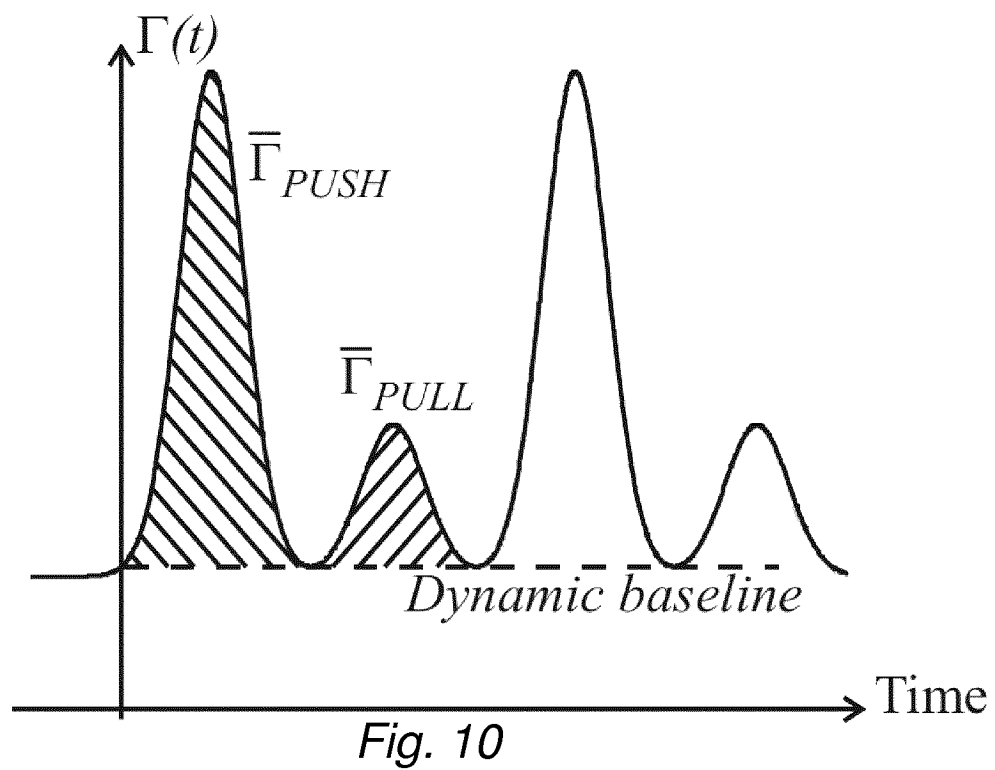
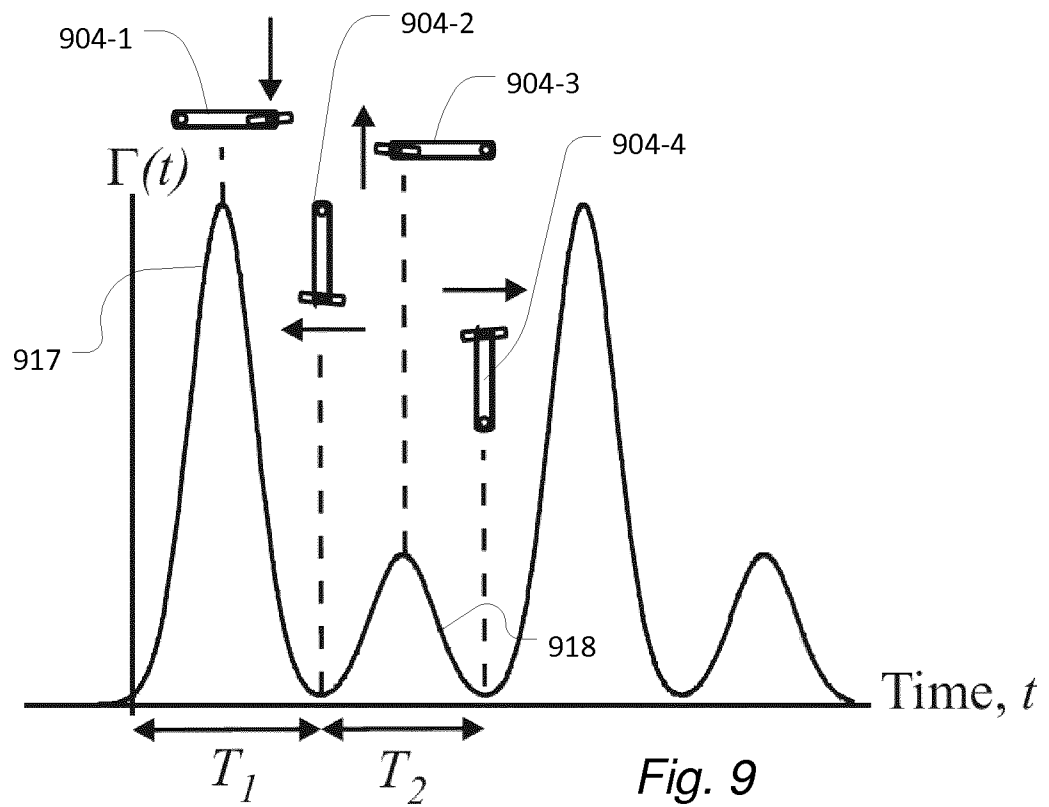


Fig. 8



5/14

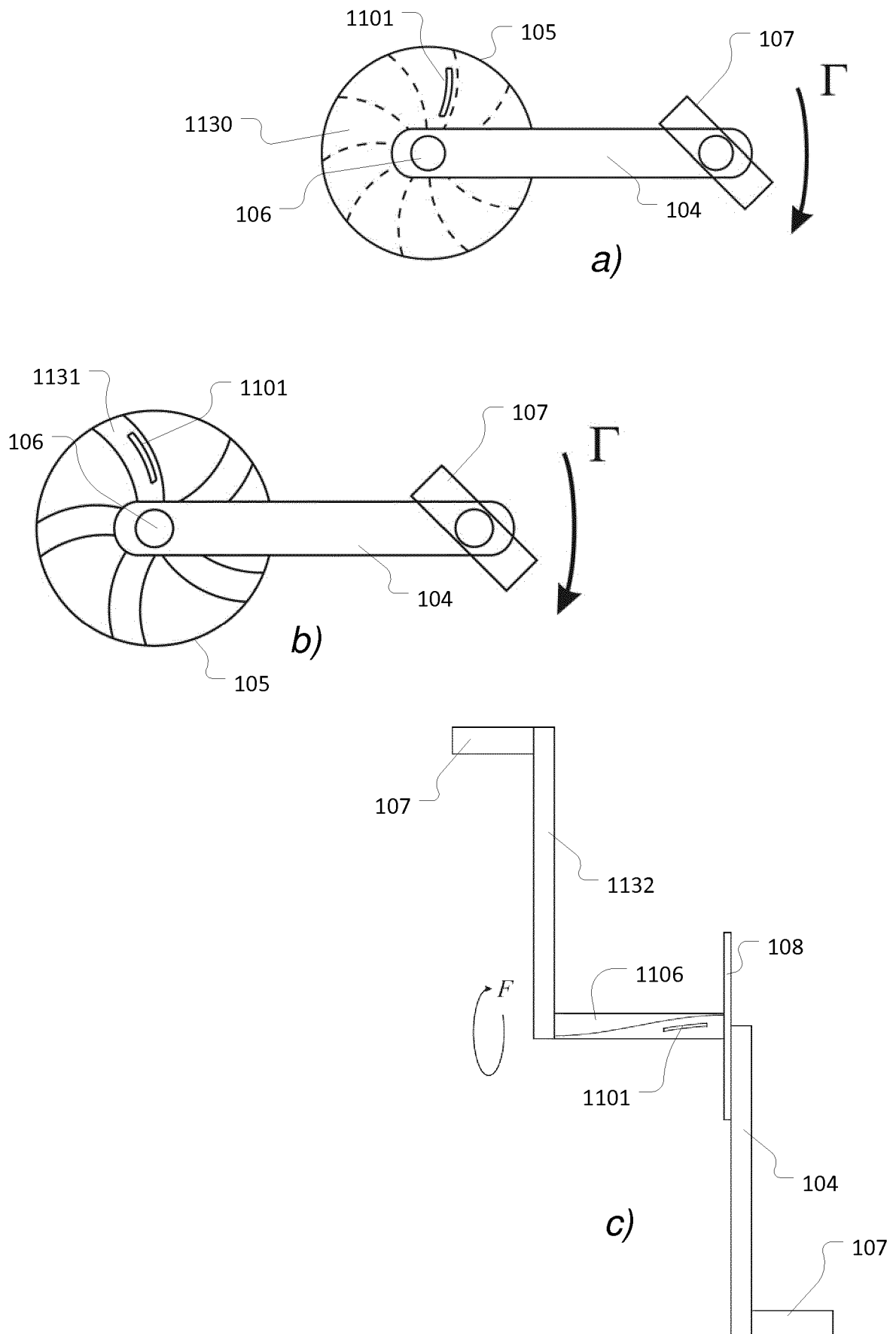
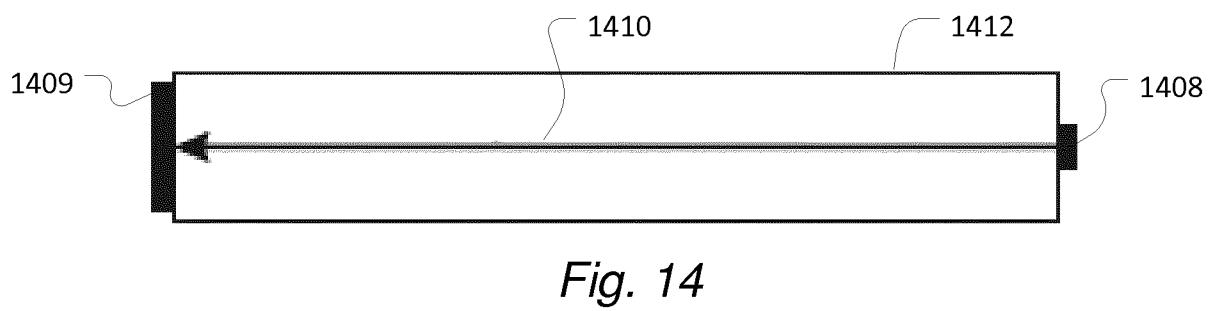
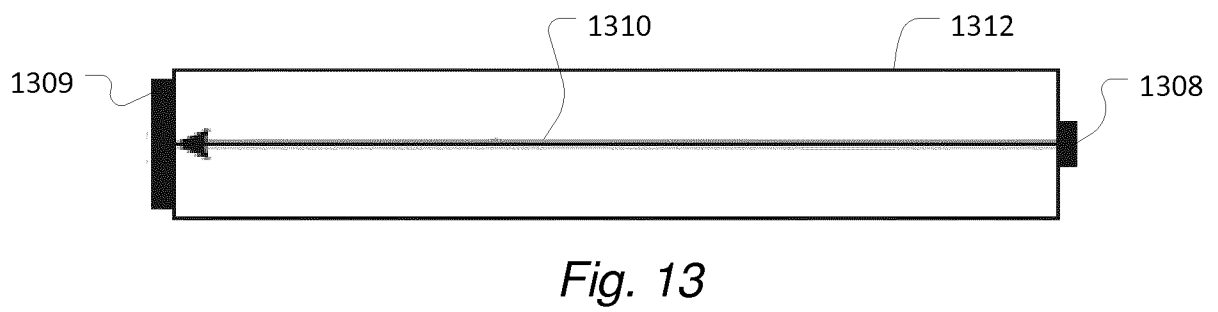
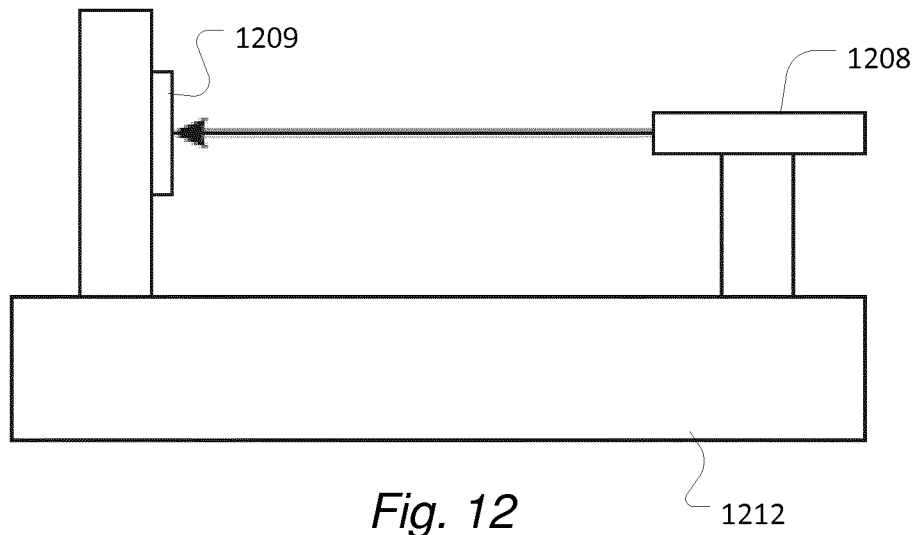


Fig. 11

6/14



7/14

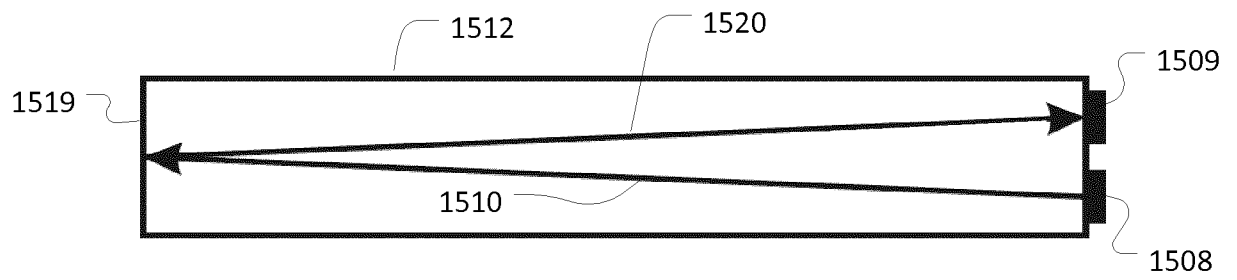


Fig. 15

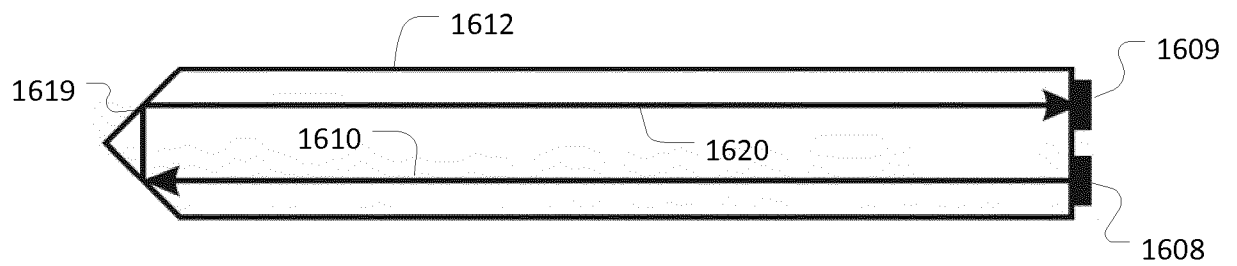


Fig. 16

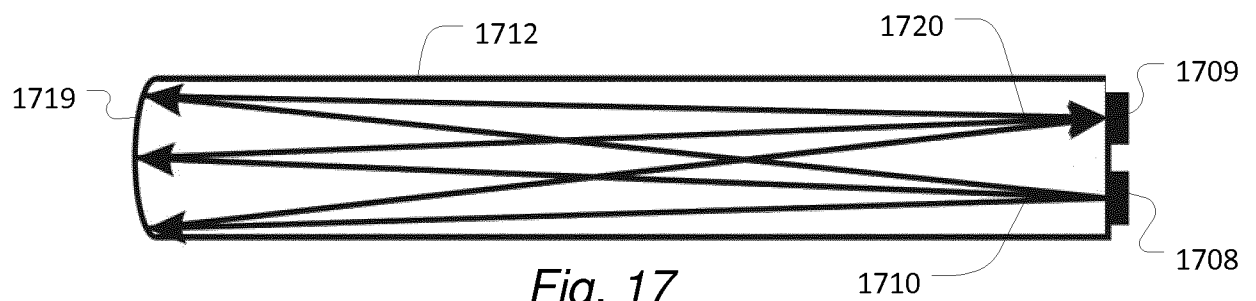


Fig. 17

8/14

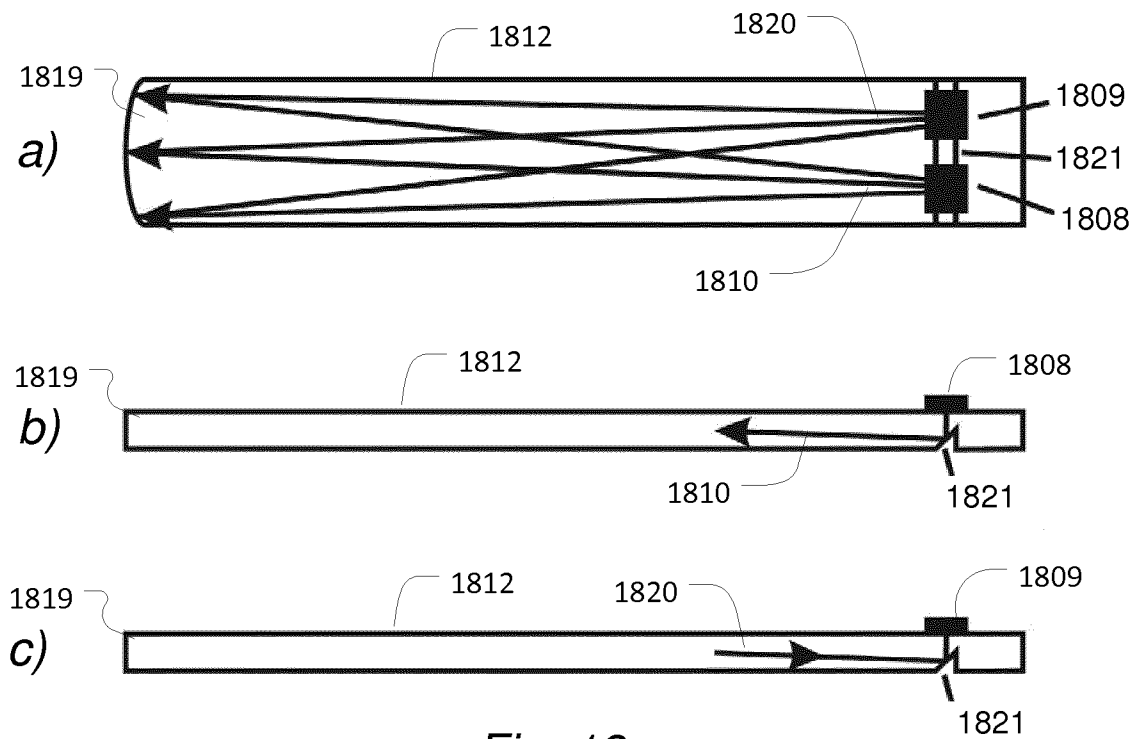


Fig. 18

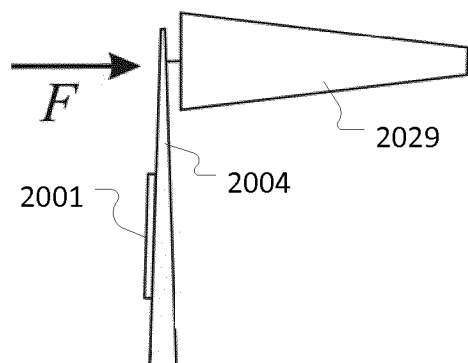


Fig. 20

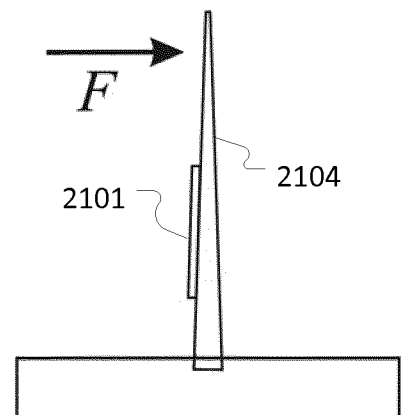


Fig. 21

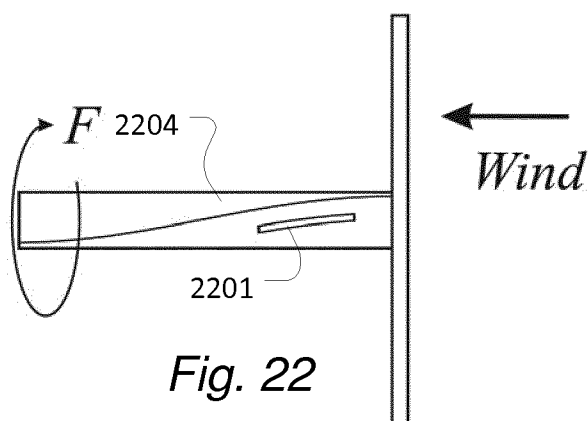


Fig. 22

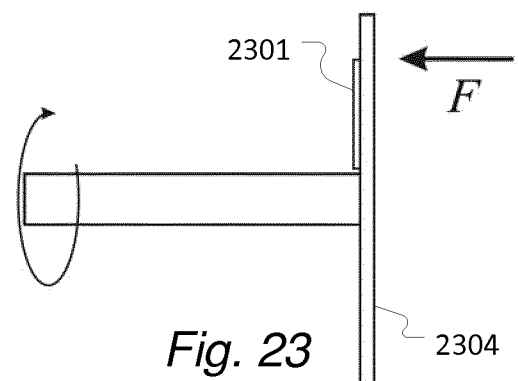


Fig. 23

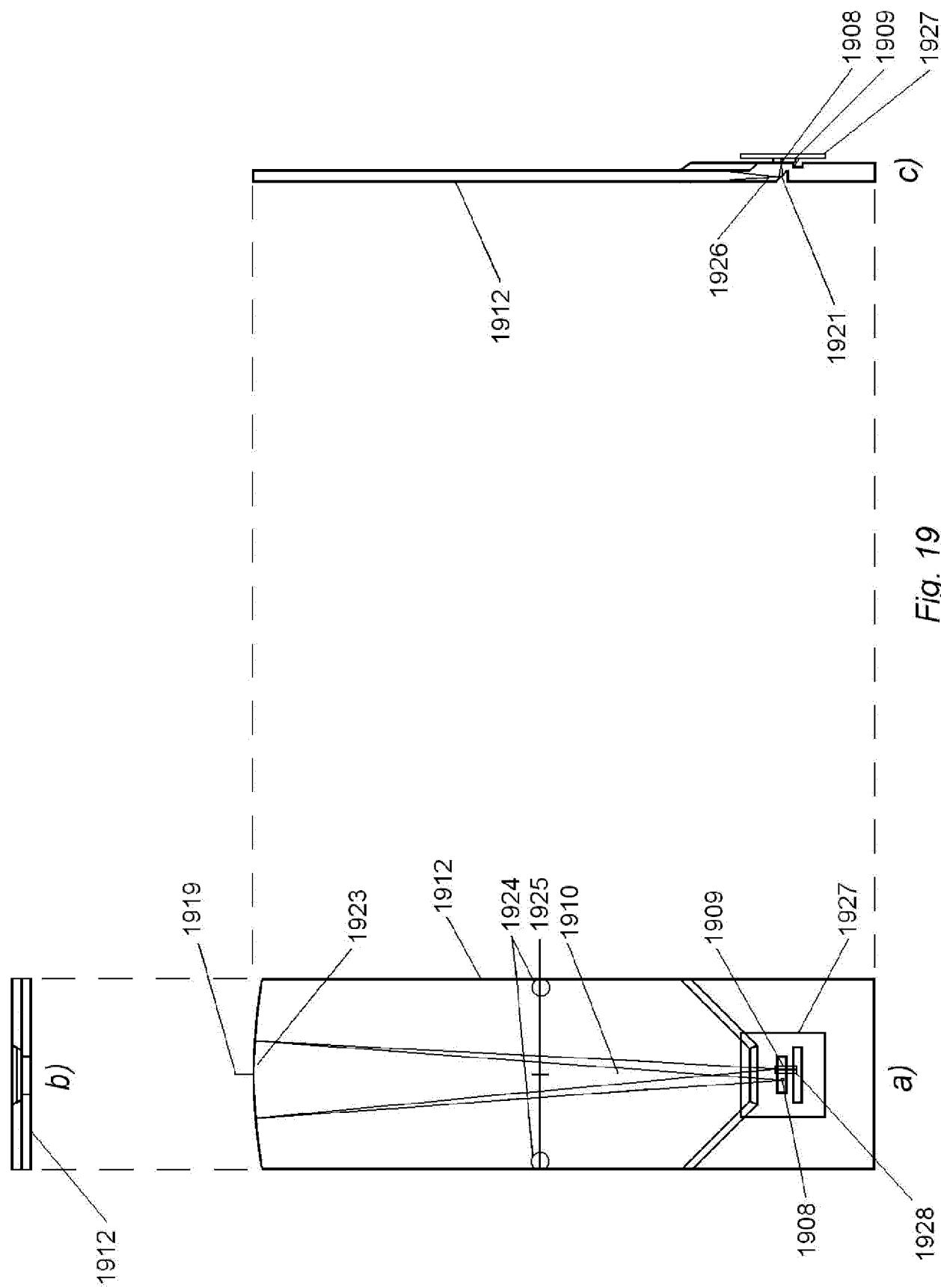


Fig. 19

10/14

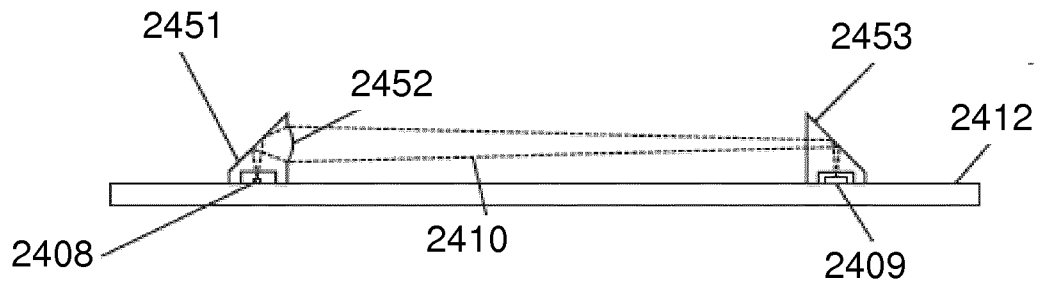


fig.24

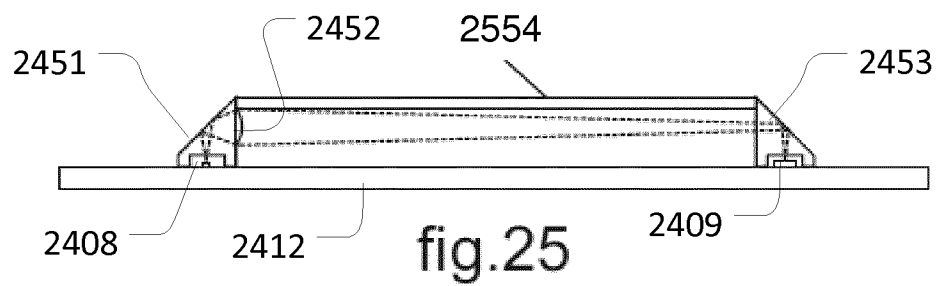


fig.25

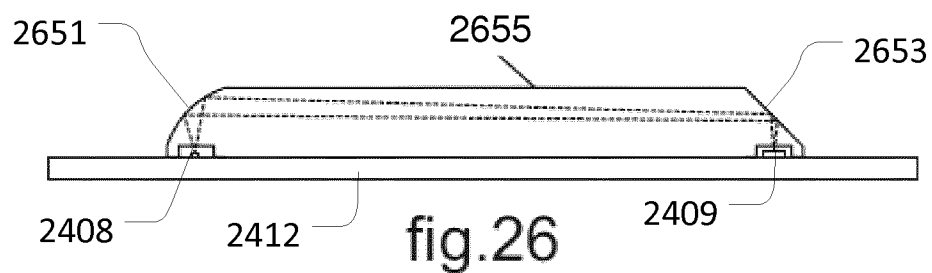


fig.26

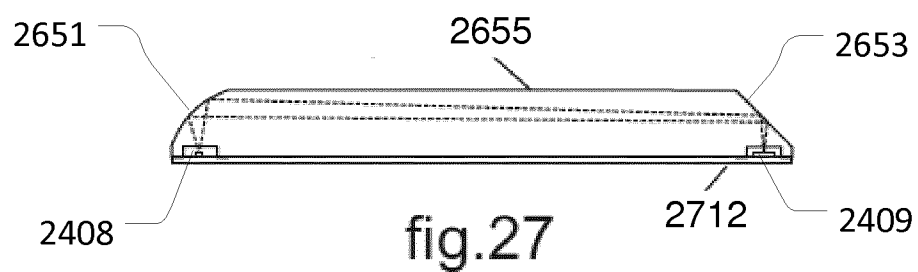


fig.27

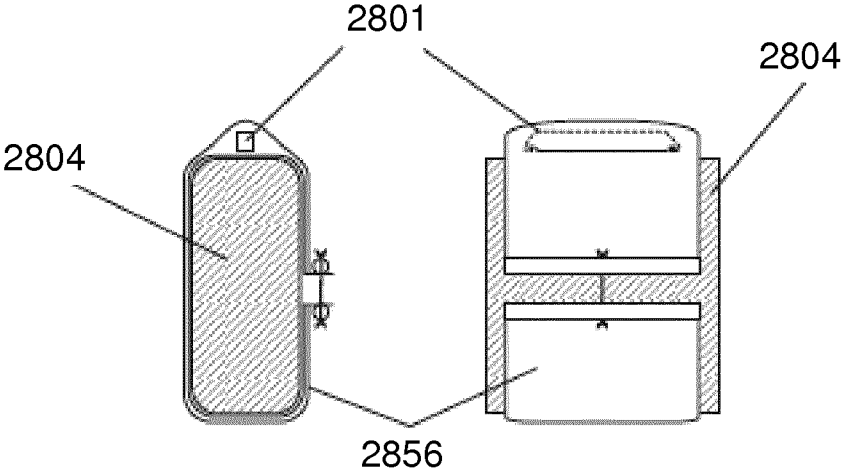


fig.28

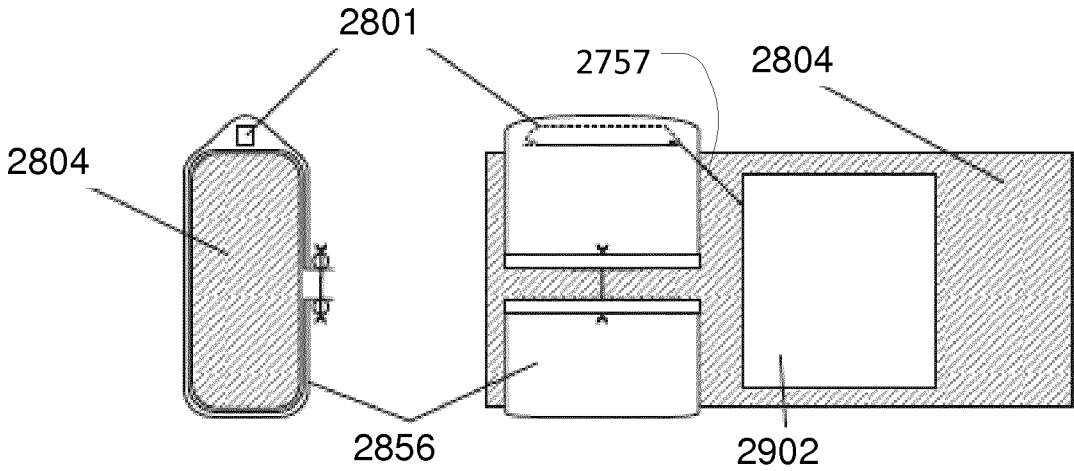


fig.29

12/14

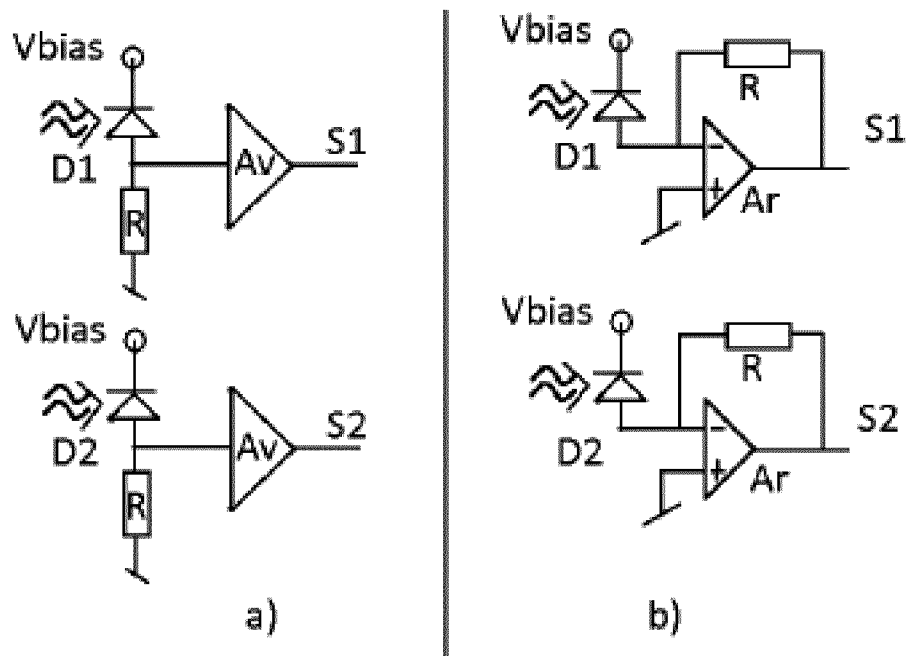


Fig. 30

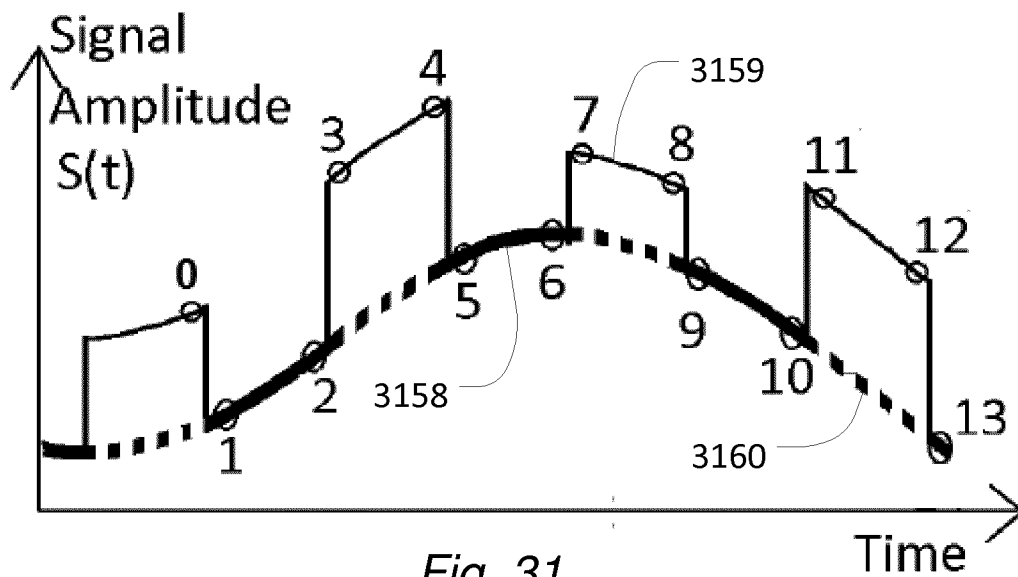


Fig. 31

```

float S[N], L[N/2];
for(int j=0; j < N/2;)
{
    L[j]    = S[j]    - S[j+1];
    L[j+1] = S[j+3] - S[j+2];
    j=j+2;
}

```

Fig. 32

13/14

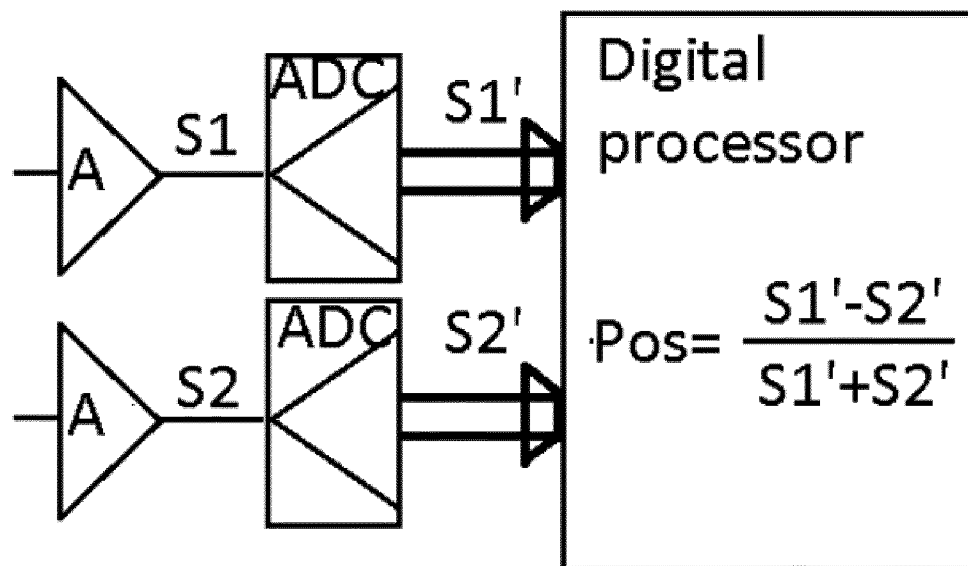


Fig. 33

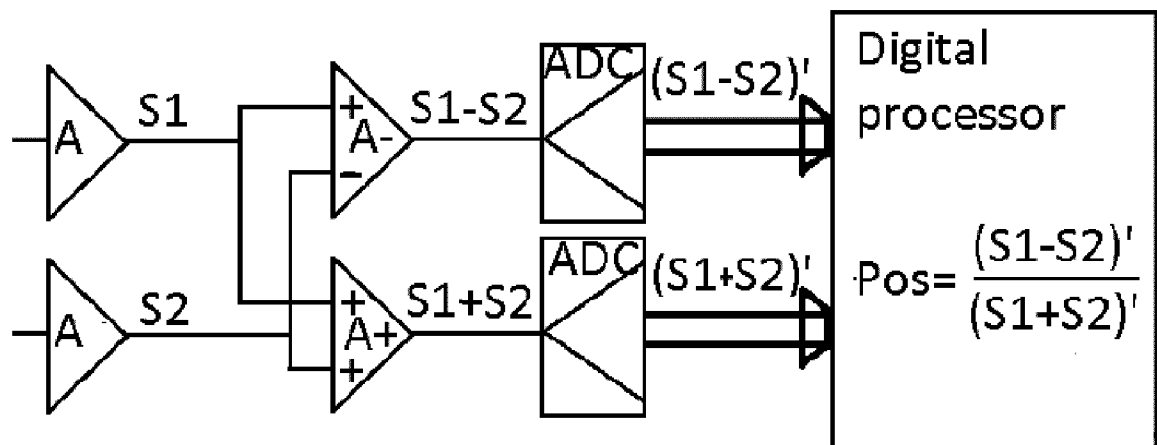


Fig. 34

14/14

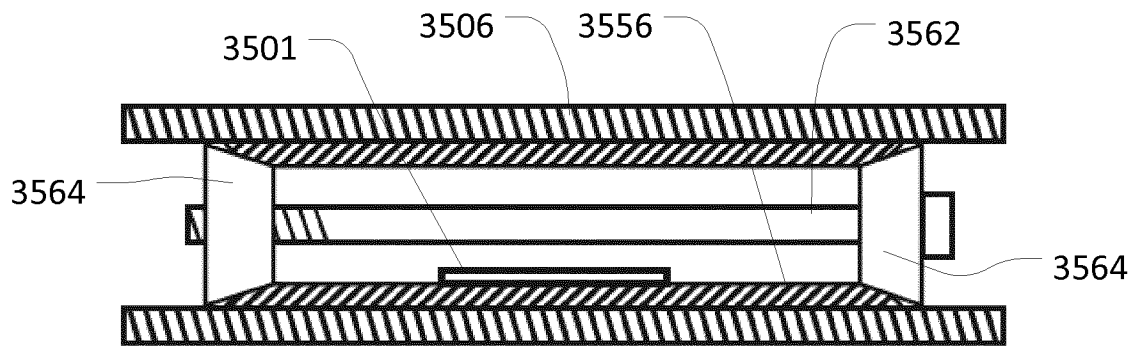


Fig. 35

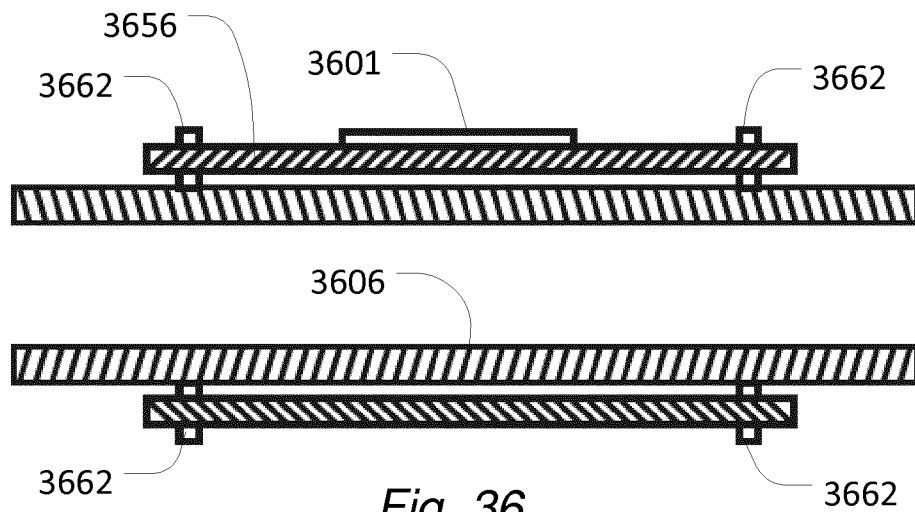


Fig. 36

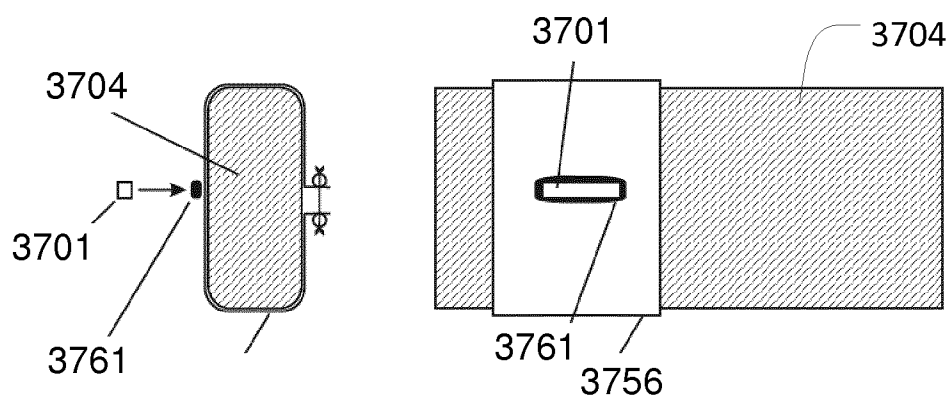


Fig. 37

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/072381

A. CLASSIFICATION OF SUBJECT MATTER INV. G01L1/24 A63B22/00 G01L3/14 G01L5/00 B62M6/50 ADD. B62M3/08		
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) G01L A63B B62M		
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) 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	CH 702 990 A1 (BMC TRADING AG [CH]) 31 October 2011 (2011-10-31)	1-6, 11-16
Y	the whole document -----	7-10
Y	US 2004/129868 A1 (KILMARTIN BRIAN [US]) 8 July 2004 (2004-07-08) abstract; figure 1 -----	7-10
A	DE 20 2004 003978 U1 (WILLE GMBH & CO KG EDUARD [DE]) 3 June 2004 (2004-06-03) the whole document -----	1-16
A	WO 2012/111007 A1 (WATTEAM LTD [IL]; DAVID ELIYAHU [IL]; GAL-ON OFIR [IL]) 23 August 2012 (2012-08-23) the whole document -----	1-16
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
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Date of the actual completion of the international search	Date of mailing of the international search report	
10 December 2013	20/12/2013	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Stavroulis, Stefanos	

INTERNATIONAL SEARCH REPORT

Information on patent family members

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