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(54) Title: FIBER-OPTIC VOLTAGE SENSOR

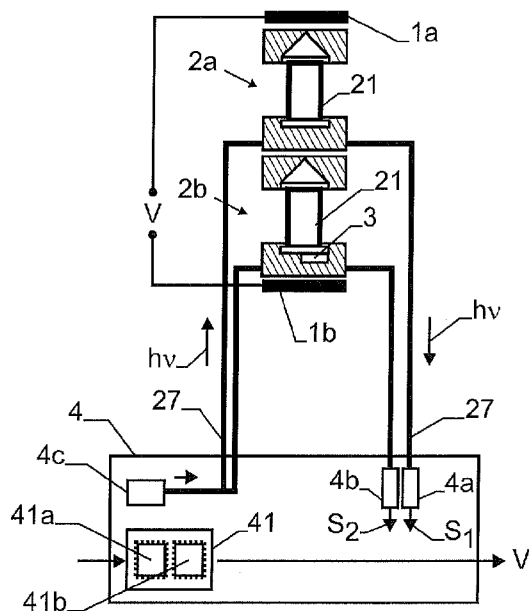


Fig. 3

(57) Abstract: A method and device for measuring a voltage (V) between two terminals (1a, 1b), in particular an AC voltage in the high-voltage regime, is disclosed. The method and/or device relies on an electro-optic effect in an electro-optical element (2; 2a, 2b, 2c). This electro-optic effect introduces, e.g., a different optical phase shift in two perpendicularly polarized light waves that travel through the electro-optical element (2; 2a, 2b, 2c). Thus, a signal (S₁, S₂) indicative of the electric field at the position or over the length of the electro-optical element (2; 2a, 2b, 2c) can be measured. Ambiguities in the signals are resolved by an additional quadrature signal. The invention discloses a method and device for accurately reconstructing the waveform of the applied voltage (V) between the terminals (1a, 1b) using a plurality of electro-optical elements, but not requiring a quadrature signal for each electro-optical element (2; 2a, 2b, 2c).



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Fiber-Optic Voltage Sensor

Technical Field

The present invention relates to a method and
5 device for measuring a voltage, in particular an AC voltage in the high-voltage range.

Introduction and Background Art

Optical high-voltage sensors often rely on
10 electro-optic effects (such as Pockels effect and/or Kerr effect) in crystalline materials such as $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) (L. Duvillaret, S. Rialland, and J.-L. Coutaz "Electro-optic sensors for electric field measurements. II. Choice of the crystal and complete optimization of their orientation" J. Opt. Soc. Am. B 19 2704 (2002)).

US 4,904,931 and US 5,001,419 disclose a sensor in which the full line voltage (up to several 100 kV) is applied over the length of a single BGO crystal (typically between 100 mm and 250 mm length). The crystal
20 class of BGO is of symmetry such that the crystal measures the line integral $\int E \cdot ds$ over the crystal length, i.e. from ground to high-voltage potential. As a result, stray fields, e.g., from neighboring phases do not influence the measurement. The applied voltage introduces a
25 differential optical phase shift between two orthogonal linearly polarized light waves propagating along parallel optical paths through the same crystal. This phase shift is proportional to the applied voltage. The light waves interfere at a polarizer at the end of the crystal. The
30 resulting light intensity varies in proportion to a DC biased cosine function of the phase shift. At typical voltages in high-voltage substations, the phase shift may correspond to several multiples of π and thus results in ambiguous sensor output. The ambiguity is resolved by
35 adding a second optical output channel to the crystal containing a quarter-wave retarder that introduces a 90° -phase offset between the interfering waves. A signal pro-

cessor reconstructs the waveform of the applied voltage from the two optical output signals at quadrature. As the electric field strength at the crystal is typically very high, the crystal is mounted in a hollow high-voltage insulator made of fiber-reinforced epoxy and filled with SF₆ gas under pressure in order to obtain sufficient dielectric strength. The insulator diameter is large enough to keep the field strength in the air outside the insulator below critical limits.

US 6,252,388 describes a voltage sensor which uses several smaller electro-optic crystals mounted at selected positions along the longitudinal axis of a hollow high-voltage insulator. The crystals measure the electric fields at their locations. The sum of these local field measurements serves as an approximation of the voltage applied to the insulator. In this case the electro-optic phase shift at each crystal is within $\pm 90^\circ$ at the rated voltage, i.e. there is no ambiguity in the sensor response.

Therefore, the high-voltage sensors of the above types have the disadvantages that either the electric field strength at the (large and therefore expensive) crystal is so high that (expensive) measures for insulation and/or field steering have to be taken or - in the case of multiple sensors - that complicated optical systems, e.g. including beam splitters and quarter-wave retarders, need to be arranged at every crystal for unambiguous and/or precise reconstruction of the voltage-signal.

US 5,247,244 discloses an electro-optic voltage measuring system in reflection and with temperature compensation. Again, the high voltage is applied along a single crystal and two optically parallel light beams are traversed through the full crystal length and are phase-shifted relative to one another. Temperature compensation is effected via measurement of capacitive current through the electro-optic crystal, and a correction factor is de-

rived and applied to the half-wave voltage and is used to calculate the instantaneous voltage value.

US 5,715,058 discloses another electro-optic sensor for measuring high voltages in a reflective setup. High voltage is applied to the crystal and the crystal is traversed forth and back by a single light beam. This light beam is split only after exiting from the crystal into two optical channels that are phase-shifted relative to one another. Temperature compensation is achieved by measuring a temperature-dependence of the phase shifting waveplate.

Disclosure of the Invention

Hence, it is a general objective of the invention to accurately measure voltages over a large range in a simple manner.

This objective is achieved by the method and the device of the independent claims. Exemplary embodiments are disclosed in the dependent claims and claim combinations.

Accordingly, at least two electro-optical light transmitting elements (sensor modules, e.g., comprising electro-optical crystals, poled waveguides, or piezo-electric devices), are arranged in the electric field between two spaced-apart terminals with the to-be-measured voltage applied to the terminals. Light, for example linearly polarized light, is then passed through the electro-optical light transmitting elements. By means of the properties of the electro-optical light transmitting elements, at least a first and a second signal indicative of the electric fields over the respective electro-optical light transmitting elements are then measured. These first and second signals are periodic functions of the applied voltage. Thus, by combining the at least two signals, the voltage between the first and the second terminal can be derived and ambiguities in the first signal are resolved using the second signal. There-

fore, as an advantage over prior art, only one second signal (from one electro-optical light transmitting element) is sufficient to resolve ambiguities in the voltage calculation based on the first signal from the other
5 electro-optical light transmitting element. This results in simpler optics which is cheaper and advantageous in terms of size.

According to the invention, the electro-optical light transmitting elements are arranged in series, i.e. electrically in series (i.e. one after another
10 along the z-axis in a longitudinal or axial direction) between the terminals. Thus, the electric field is distributed over the single electro-optical light transmitting elements, which leads to simpler insulation and
15 cheaper implementation.

In embodiments, the first and the second signals have the same periodicity of the voltage V or are scaled such that they have the same periodicity of the voltage. Furthermore, the first and second signals have a
20 mutual phase shift other than zero, i.e., the phase of the second signal is shifted with respect to the phase of the first signal. In embodiments, the nonzero phase shift of the second signal with respect to the first signal is introduced by a phase shifting element which is arranged
25 in an optical path at the second electro-optical light transmitting element. This phase shifting element is, e.g., a $\lambda/4$ retarder and thus a quadrature readout is enabled.

In embodiments, the phase shift of the second
30 signal with respect to the first signal is dependent on the temperature of the phase shifting element. Thus, in a preferred embodiment, the temperature of the phase shifting element can be derived from the second signal. This derived temperature can then, for example, be used for
35 computational compensation of a temperature dependence of the measured signals and hence for a computational compensation of the temperature dependence of the derived

voltage between the first and the second terminal. Thus, a better accuracy can be provided.

In embodiments, the two signals are based on electric field-dependent changes of a physical property of the light beams, for example the phase of two orthogonal linearly polarized light waves per electro-optical light transmitting element. Then, e.g. after interference of these light waves at a polarizer at the end of each electro-optical light transmitting element, the resulting light intensity signals are converted to an electrical signal per crystal, e.g., by photodiodes.

The to-be-measured voltage between the terminals is in particular an AC voltage and/or in the high-voltage range, in particular in the range between 75 kV and 800 kV or even more. Thus, voltages in substations of power transmission networks can be measured.

After a first time interval $[t_1; t_2]$ with voltage ranges leading to a periodicity of the measured signals as functions of the voltage (i.e. the whole period of the measured signals is covered, or, in other words, the measured signals as periodic functions of the voltage reach their maximum and minimum values), an advantageous embodiment of the disclosed method and/or device is also suitable for measuring small voltages during a second time interval $[t_3; t_4]$. The term "small voltage" refers to a range of voltages that is too small for the measured signals to reach their maximum and minimum values (i.e. to cover the full period of the measured signals). This is advantageous in the case of a voltage-drop due to, e.g., a malfunction in the power transmission network. The time gap $(t_3 - t_2)$ between the first time interval and the second time interval is larger than one voltage signal period to enable "small voltage" detection. Then, scale and/or offset parameters that has or have been derived during the first time interval $[t_1; t_2]$ is or are kept constant for deriving the voltage V between the terminals during the second time interval $[t_3;$

t4]. Thus, an accurate deriving of the voltage is possible even for voltage ranges that do not cover the full period of the measured signals.

In a preferred embodiment, only one signal
5 per electro-optical light transmitting element is measured. This results in simpler optics.

In another preferred embodiment, at least one internal parameter α_n , e.g., the fraction of the total voltage V that is applied to a single electro-optical
10 light transmitting element (or another value descriptive of a distribution of the voltage over the electro-optical light transmitting elements), is recursively derived based on its most common value. Due to a recursive tracking of the internal parameter α_n , its exact values are
15 not needed during a first initialization.

In another advantageous embodiment the step of resolving the ambiguity in the first signal comprises a step of taking a binary decision between two hypotheses. These hypotheses correspond to different possible
20 voltage values given the measured value of the first signal. The binary decision further comprises a derivation of an expected value of the second signal for each of the hypotheses and a comparison of the expected value to a measured value of the second signal. Thus, an unambiguous
25 solution can be found.

In another preferred embodiment, at least three electro-optical light transmitting elements are arranged in series in the electric field between the terminals and at least three signals indicative of the electric fields over the respective electro-optical light
30 transmitting elements are measured. By combining all signals, the voltage between the first and the second terminal can be derived. In this process, ambiguities in all signals can be resolved.

35 Furthermore, a device which is adapted to carry out a voltage measurement by means of a method according to the invention is provided.

Brief Description of the Drawings

The invention will be better understood and objectives other than those set forth above will become apparent when consideration is given to the following detailed description of the invention. This description
5 makes reference to the annexed drawings, wherein:

Fig. 1 (prior art) shows a schematic representation of an optic voltage sensor,

Fig. 2a, 2b, 2c show different configurations
10 for electro-optical voltage sensors,

Fig. 3 shows an arrangement of two electro-optical light transmitting elements in the electric field between two terminals,

Fig. 4 shows a flowchart of a method for measuring a voltage between a first and second terminal with a plurality of electro-optical light transmitting elements,
15

Fig. 5 shows a signal with period numbers,

Fig. 6 shows a disambiguation procedure using a quadrature signal,

Fig. 7 shows a procedure to measure a phase,
20

Fig. 8 shows a method for locating returning points of a voltage signal,

Fig. 9 shows an arrangement of three electro-optical light transmitting elements in the electric field between two terminals.
25

Modes for Carrying Out the Invention

A method and device for measuring a voltage between two terminals, in particular an AC voltage in the high-voltage regime, is disclosed. In embodiments, the
30 method and/or device relies on an electro-optic effect in an electro-optical element. This electro-optic effect introduces, e.g., a different optical phase shift in two perpendicularly polarized light waves that travel through the electro-optical element. Thus, a signal indicative of
35 the electric field at the position or over the length of the electro-optical element can be measured. Ambiguities

in the signals are resolved by an additional quadrature signal. By arranging a plurality of these electro-optical elements in series between the terminals, advantages in terms of cost efficiency and insulation are achieved, but resolving the ambiguities of the signals becomes more challenging, particularly for unequal and/or varying voltages over the single electro-optical elements (and consequently unequal periodicity of the measured signals) as well as varying relative phases of signals. The invention discloses a method for accurately reconstructing the waveform of the applied voltage between the terminals using a plurality of electro-optical elements but not requiring a quadrature signal for each electro-optical element. Furthermore, the temperature of the system can be derived from the phase of the quadrature signal and it can be used to compensate for the temperature dependence of the electro-optic effect itself. Furthermore, a method for deriving a small voltage (i.e. the voltage being much smaller than the rated voltage and the electro-optic phase shift being within $\pm 180^\circ$) is disclosed. Furthermore, a device for measuring a high-voltage is disclosed.

Definitions:

The term "high voltage" designates AC voltages exceeding 1 kV or DC voltages exceeding 1.5 kV and, in particular, voltages exceeding 75 kV.

The terms "radial" and "axial" are understood with respect to the axial direction (parallel to the axis of the light beam $h\nu$, z-axis) of the sensor, with "radial" designating a direction r perpendicular to the axial direction and "axial" designating a direction parallel to the axial direction z .

Description of the invention:

As shown in Fig. 1 (prior art), an electro-optical light transmitting element 2 comprises an optical sensor 21 (e.g. an electro-optic crystal) introducing a

field-dependent phase shift between a first polarization or mode and a second polarization or mode of light passing through it. This light can, e.g., be guided to the optical sensor 21 through an optical fiber 27 and a coupling lens 26. Ideally, an electro-optical light transmitting element 2 measures the path integral $\int E \cdot ds$ of the electric field between two electric potentials 1a, 1b, e.g. ground 1a and high voltage potential 1b. This concept is particularly suited for outdoor installations, e.g. substations in power transmission networks, because the measurement accuracy is not deteriorated by field perturbations, e.g. due to rain or ice or crosstalk from neighboring phases. Electro-optic crystals 21 of certain symmetry are well suited to implement this concept.

15 An electric field applied to an electro-optical crystal 21 induces an anisotropic change in the refractive index of the material (birefringence). This birefringence (or change of birefringence) causes a phase shift between two orthogonally linear polarized light waves traversing the crystal 21 (Pockels effect). By measuring this phase shift, the applied voltage can be derived. One configuration of an electro-optical light transmitting element 2, which implements line integration of the electric field, is shown in Fig. 1: The voltage V is applied to the end faces of a crystal 21 with the light also entering and leaving the crystal through the end faces. The crystal material and its axis orientation are chosen such that only electric field components E_z (pointing along the cylinder) contribute to the electro-optic phase shift.

25 One suitable material is $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) in a [001] configuration, corresponding to the 4-fold crystal axis being parallel to the direction of light propagation. The input light $h\nu$ (broad arrow) is linearly polarized by a first polarizer 22 (thinner arrows indicating the direction of a transmitted polarization; the first polarizer 22 may be an in-fiber polarizer, as well). To achieve maximum modulation contrast, the electro-optic axes of

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the crystal x' , y' are preferably oriented under an angle of 45° with respect to the incoming linear polarized light. The phase shift Γ between the components of the light with polarizations parallel to x' and y' is caused by the electric field in the crystal 21 and is converted to an amplitude modulation of the transmitted light by a second polarizer 23 arranged at the output end of the crystal 21. To bias the phase shift Γ , an additional phase shifting element 3 (adding a phase ϕ) may be placed in the optical path (between the two polarizers 22, 23). The principal retarder axes e_1 and e_2 are aligned parallel to the electro-optic axes x' and y' of the crystal 21. In general, the intensity I of the transmitted light after the second polarizer 23 is of the form $I \sim \cos^2(V)$. The retarder 3 is, for example, a $\lambda/4$ waveplate.

For typical voltages V at high-voltage substations, an ambiguous sensor response is usually achieved. This ambiguity is classically resolved by working with two optical output channels per crystal that are substantially 90° ($\pi/2$) out of phase (i.e., that are in quadrature) or that have any other mutual phase shift that is not a multiple of π . The 90° -phase shift may be generated by splitting the light that leaves the crystal into two paths by means of a beam splitter 24 and a deflection prism 25 and arranging a phase shifting element 3 in one of the paths (Fig. 2a).

In a voltage sensor comprising at least a first and a second electro-optical light transmitting element 2a and 2b (Fig. 3), a quadrature signal S_2 may be generated by inserting a phase retarder 3 into the optical path at one of the electro-optical light transmitting elements (here: electro-optical light transmitting element 2b as in Fig. 2c) and operating the other electro-optical light transmitting element(s) (here: electro-optical light transmitting element 2a as in Fig. 2b) without a retarder. As a consequence, there is only one output channel per crystal (as in Figs. 2b and 2c). Extra

beam splitters 24 and deflection prisms 25 for a quadrature channel per crystal 21 (as in Fig. 2a) are thus avoided. As a result the device becomes significantly smaller (and cheaper), which allows to mount the sensing
5 elements in a relatively narrow bore.

In the shown embodiment, light is guided to and from the electro-optical light transmitting elements 2a, 2b through optical fibers 27. The light is usually produced by a light source 4c (e.g. an LED or a laser)
10 inside a light processing module 4. Transmission light is detected inside the light processing module 4 by a photodetector 4a, 4b, such as a photodiode, per channel, which means here, e.g., per electro-optical light transmitting
15 element 2a, 2b due to a single channel being present per element. Alternatively, the photodetectors 4a, 4b could be integrated into the electro-optical light transmitting elements 2a, 2b themselves. A first and a second signal S_1 and S_2 which are indicative of the electric field over the respective electro-optical light transmitting element
20 2a and 2b are thus measured. A control unit 41 (consisting of a CPU 41a and a memory 41b) derives the voltage V between the terminals 1a and 1b based on the signals S_1 and S_2 . During the derivation, ambiguities in a single signal - or, in the case of more than two signals, ambiguities in a subset of the signals - are resolved by the
25 quadrature signal S_2 . In other words, all pairs of measured signals produce an unambiguous output, in particular if one of, preferably exactly one of, the signals is phase-shifted with respect to the other. Therefore, it is
30 possible to measure only one signal S_1 and S_2 per electro-optical light transmitting element 2a and 2b and nevertheless to arrive at an unambiguous voltage signal V . This results in simpler optics, which is cheaper and advantageous in terms of size.

35 The voltage sensor shown in Fig. 9 is very similar to the voltage sensor discussed above, with the exception that it comprises an additional, e.g. a third,

electro-optical light transmitting element 2c from which a third signal S_3 is measured via a third photodetector 4d.

5 The procedure for accurately reconstructing the waveform of the applied voltage V (even under unequal and varying partial crystal voltages V_n , and consequently under unequal periodicity of the optical signals S_n) as well as under varying relative signal phases is summarized in Fig. 4.

10 The procedure starts with an initialization stage, where (not necessarily accurate) initial values α_n , V_n , Δ_n are set for each electro-optical light transmitting element (see below). These parameters might be determined in a (semi-)automated way or provided manually
15 by the operator. Then, for each measured signal S_n (e.g., from photodiodes 4a, 4b, ...) representing a light intensity level I from each electro-optical light transmitting element 2a, 2b, ..., it is verified whether the applied voltage is "large", i.e. an electro-optic phase shift
20 $>\pm 180^\circ$ is induced or, in other words, the absolute value of the electro-optic phase shift exceeds 180° , or in general whether the signal(s) reaches a minimum and a maximum, or "small", i.e. the electro-optic phase shift remains within $\pm 180^\circ$ or, in other words, the absolute value
25 of the electro-optic phase shift is smaller than or equal to 180° , or in general whether the signal(s) does not reach a minimum and a maximum. When the voltage is "large", the amplitude of the acquired signal S_n is normalized to a given interval, e.g. to the interval $[-1;1]$,
30 in order to eliminate gain and offset differences amongst the channels due to the measurement chain (here e.g. photodiode - amplifier). When the voltage is "small", the signal S_n is not normalized in order to preserve the correct information about amplitude, and thus about the applied
35 voltage (see below).

Then, the partial voltage V_n applied to each electro-optical light transmitting element 2a, 2b, ... is

determined from S_n in two steps: The first step is to count the zero-crossings in S_n , as it is illustrated in Fig. 5. This is used to determine the period K of the co-sinusoidal response and provides a first, coarse approximation of the applied voltage V_n . This approximation can then (if necessary) be refined by computing the remainder or approximation error, which is given by the inverse response (usually the arccosine function) of the sensor. The sum of the zero-crossings approximation and of the remainder gives the applied voltage V_n .

The total voltage V between the terminals 1a and 1b is finally given by the sum of all partial voltages V_n : In the embodiment of the invention from Fig. 3, the high-voltage sensor is composed of several electro-optical light transmitting elements 2a, 2b. Each electro-optical light transmitting element 2a, 2b consists of an insulator with a central bore containing, e.g., a BGO crystal 21. The total voltage between terminals 1a and 1b is denoted by V . The partial voltage applied to a given electro-optical light transmitting element 2a, 2b, ... is denoted by V_n . The total voltage V is then the sum of all partial voltages: $V = \sum V_n$. Conversely, partial voltages V_n are defined by the fraction α_n of the total voltage V that is applied to the corresponding module: $V_n = \alpha_n \cdot V$. As mentioned earlier, partial voltages might differ and vary in time. Therefore, $\alpha_n \neq \alpha_m$ if $n \neq m$ and $\alpha_n = \alpha_n(t)$. The intensity I of the light beam exiting each electro-optical light transmitting element 2a, 2b, ... is given by the following expression:

$$I_n = I_{n,0} \cdot \cos^2(\pi(\Gamma_n + \Lambda_n)) \quad (1)$$

$$\Gamma_n = \frac{V_n}{2V_{h,n}} \quad (2)$$

where $I_{n,0}$ is the intensity of the exiting beam with zero retardation, Γ_n expresses the retardation (field-dependent phase shift) between the two polarized light

components when they exit the crystal 21, and Δ_n is the relative phase of the signal. $V_{h,n}$ is the half-wave voltage of the BGO crystal 21 in optical path n. This is the voltage that leads to the retardation of $\Gamma_n=1/2$. In equation (1), it is assumed that the modulation depth of the optical signal is equal to unity. The relative phases Δ_n of the signals can differ and vary in time depending on temperature, as mentioned earlier. Therefore, $\Delta_n \neq \Delta_m$ if $n \neq m$ and $\Delta_n = \Delta_n(t)$.

The electrical signals S_n produced by the measurement chain (photodiode - amplifier) is then given by

$$S_n = G_n \cdot I_n + b_n + e_n \quad (3)$$

where G_n is the cumulated gain of all components in the measurement chain, and b_n is an offset. The term e_n is a noise term.

Measurement of the applied voltage

As mentioned above, in the first signal processing stage (Fig. 4), the amplitude of each electrical signal can be normalized to the interval $[-1; 1]$. This operation eliminates the gain and offset parameters from equation (3) (the noise term e_n has been neglected here):

$$S_n^{Norm} = 2 \cdot \cos^2(\pi(\Gamma_n + \Delta_n)) - 1 \quad (4)$$

Signal normalization is simply achieved by applying the scale and offset factors that map the minimum or maximum of the actual response to the desired, normalized minimum or maximum (i.e., -1 and 1):

$$scale = 0.5 \cdot (max - min) \quad (5)$$

$$offset = min + scale \quad (6)$$

$$S_n^{Norm} = \frac{S_n - offset}{scale}$$

(7)

To solve the above equations, both response extrema min (=minimum) and max (=maximum) shall be determined. This means in turn that response normalization can only be done when the electro-optic phase shift induced by applied voltage between the terminals 1a and 1b is above $\pm 180^\circ$, i.e. a "large" voltage is measured. Otherwise, the scale and offset factors must be kept constant until the above condition is fulfilled again (see "Measurement of small voltages" below). In the second stage, all partial voltages V_n are determined by solving equations (1)-(4) for V_n . This leads to

$$V_n = \frac{V_{h,n}}{\pi} \left(\left(\pm \arccos \left(\frac{2(S_n - b_n)}{G_n \cdot I_{n,0}} - 1 \right) + K \cdot 2\pi \right) - 2\pi \Delta_n \right) \quad (8)$$

Note that after signal normalization, $G_n=1$ and $b_n=0$. In equation (8), it is apparent that due to the periodicity of the (arc-)cosine, V_n can only be resolved up to the factor $2K \cdot V_{h,n}$ when K = number of periods is unknown. In order to determine K , i.e. the number of periods of the sinusoidal response of the electro-optical light transmitting element that corresponds to the applied voltage V_n , a bidirectional count k of the number of zero crossings of the measured signal S_n is used. In fact, the number k of zero crossings changes twice per period K . The zero-crossings counting procedure is derived from US 5'001'419, which in its entirety is herewith made part of the disclosure by reference. Two optical signals at quadrature are considered: The count k is incremented as the voltage waveform represented by the base signal is becoming more positive and is decremented as the magnitude of the represented waveform is becoming more negative. The base signal is the signal for which the parameter of interest, e.g. here the number of zero crossings, is determined. The quadrature signal is another signal -

in our case from a different electro-optical light transmitting element 2a, 2b, ... - that has been delayed with respect to the base signal, e.g. by using a phase shifting element 3. The direction in which the waveform is moving is determined by which of the signals (base signal or quadrature signal) is leading. Reversal of the direction of the voltage waveform results in a switch in which one signal is leading and can therefore be detected by two consecutive zero crossings in the same signal.

10 In order to avoid random indexing of the bidirectional cumulative count k of zero crossings, which could occur with small signals, a dead band is created around the zero axis. Zero crossings are not counted while the signal is in this dead band. Instead, a determination is made when the signal again leaves the dead band as to whether the zero crossings should be indexed:

- If the signal exits the dead band on the same side that it entered, then the target signal has changed direction and k should not be indexed;
- 20 • if the signal exits the dead band on the opposite side from which it entered, then there has been a zero crossing and k is indexed.

Note that if the zero crossings counter k can be set to zero when the voltage is zero, then subsequent voltage measurements will be correct. In general, however, the voltage at startup (during the initialization) is not known and therefore k is arbitrary. Under the assumption that the applied voltage is purely AC, k can be adjusted in integer steps until the average value of the calculated voltage over one cycle is zero. After k has been properly adjusted, the calculated voltages will be correct until the program is interrupted.

It is apparent in equation (8) that measured voltage V_n is given by the sum of two distinct terms. The first term, $K \cdot 2n$, is approximated using cumulative zero crossings counting k as discussed above. Computation of

the second term, $\arccos(2(S_n - b_n)/(G_n \cdot I_{n,0}) - 1)$, will be discussed next: Fundamentally, equation (8) must be solved for V_n given the signal S_n , with K = number of periods known from zero-crossings counting k . The sign of the arccosine cannot be determined from S_n alone. Therefore, the quadrature signal is additionally used in order to disambiguate the sign. The corresponding procedure is illustrated in Fig. 6. First, two hypotheses h^+ and h^- are generated:

$$h^+ : V_n^{h^+} \propto +\arccos(\cdot)$$

$$h^- : V_n^{h^-} \propto -\arccos(\cdot)$$

The voltage V_n under both hypotheses, $V_n^{h^+}$ and $V_n^{h^-}$, is then calculated using equation (8). Subsequently, the quadrature signal response under both hypotheses, $S_n^{h^+}$ and $S_n^{h^-}$, is computed. This is done by inserting $V_n^{h^+}$ and $V_n^{h^-}$ into the following expression, derived from equations (1)-(4):

$$S_{n'}^h = G_{n'} \cdot I_{n',0} \cdot \cos^2 \left(\pi \left(\frac{V_{n'}^h}{2V_{h,n'}} + \Delta_{n'} \right) \right) + b_{n'} \quad (9)$$

Note that in equation (9), n' is the index of the quadrature signal (e.g., $n'=2$) that is used to disambiguate the sign, not the index n of the signal whose voltage is computed: $n' \neq n$. Finally, the hypothesis with the calculated quadrature signal response $S_{n'}^h$ (expected value) that is closest (in terms of Euclidean distance) to the measured quadrature signal response $S_{n'}$ is validated.

As mentioned above, the sign of the arccosine is disambiguated by "projecting" both voltages $V_n^{h^+}$ and $V_n^{h^-}$ onto the quadrature response in order to verify which hypothesis produces an image that matches the measured quadrature signal most closely. Since it is possible that the voltage fractions applied to the base channel and to the quadrature channel differ ($\alpha_n \in [0;1]$), it is

necessary to normalize one signal with respect to the other prior to comparison. This is achieved by expressing one response as a function of the other one:

$$\begin{aligned}
 V_n &= \alpha_n \cdot V \\
 V_{n'} &= \alpha_{n'} \cdot V \\
 \Rightarrow V_{n'} &= \frac{\alpha_{n'}}{\alpha_n} \cdot V_n
 \end{aligned} \tag{10}$$

Specifically, the signals are scaled to have the same periodicity of the voltage, i.e. the base voltage V_n is normalized with respect to the quadrature voltage $V_{n'}$ prior to the computation of S_n^{h+} and S_n^{h-} .

Determination of the alphas

It has been mentioned earlier that partial voltages might be unequal and varying in time. I.e., $\alpha_n \neq \alpha_m$ if $n \neq m$ and $\alpha_n = \alpha_n(t)$. The partial voltage applied to each electro-optical light transmitting element 2a, 2b, ... can be determined by rewriting the definition of α_n :

$$\alpha_n = \frac{V_n}{V} \tag{11}$$

In equation (11), α_n is calculated using the measured partial voltages V_n and the total voltage V . On the other hand, the α_n must be known in order to compute V_n , and thus V , using equation (8). This means that in general, α_n must be known in order to compute V_n and V , and the voltages are required to compute α_n .

However, this apparent contradiction is loosened by observing that in the measurement of the applied voltage, the purpose of α_n is only to disambiguate the sign of the arccosine. Specifically, compensation for different α_n is done prior to the data association step illustrated in Fig. 6. Since the outcome of this step is a binary decision, i.e. positive or negative sign, the decision will be correct even with slightly erroneous α_n as long as the measured quadrature signal response S_n' is

"much closer" to one calculated signal response S_n^h than to the other one.

With AC voltage, the above observation implies that most of the time (or equivalently, for most voltages V_n), the $\alpha_n = f(V_n(t))$ calculated using equation (8) will be correct. α_n will only be erroneous when V_n , and thus V , is wrong due to an incorrect hypothesis selection. Therefore, α_n is correct "most of the time" or, equivalently, the correct α_n is given by most common value or mode of α_n .

α_n tracking control loop

Normally, the exact α_n are not known during initialization. In fact, they are usually not known at any time because α_n depend on stray fields, mechanical variations of the sensor, etc. Therefore, the auxiliary control loop should be initialized with an estimate of α_n for all optical channels n . Then, a first series of measurements is taken and based on the resulting V_n , more exact α_n are calculated using equation (11) and the mode of the α_n . These new estimates of α_n are used for the following calculations of V_n , which are in turn used to refine α_n , etc. Thus, α_n are converging.

The above describes an auxiliary control loop that tracks the α_n based on incoming voltage measurements. The optimal refresh rate of the control loop must be determined experimentally; however, it is expected to correspond to a few periods of the applied (AC) voltage.

Measurement of delta and extraction of the retarder temperature

The actual retardation introduced by the phase shifting element 3 varies (approximately linearly) with temperature, whereas the temperature dependence of the phase of the optical channels without retarder is weak. Therefore, the temperature of the retarder can be extracted from the phase difference between the quadrature

signal S_2 (with phase shifting element 3) and the base signal S_1 (without retarder). This information will in turn be used to compensate the sensor output for the temperature dependence of the electro-optic effect.

In order to measure the relative signal phase Δ_n for any channel n , equation (8) is solved for Δ_n when $V_n=0$ (therefore, $k=0$), as illustrated in Fig. 7. With the normalized signal ($G_n=1$ and $b_n=0$), this leads to the following expression:

$$\Delta_n = \pm \frac{V_{h,n}}{2\pi^2} \arccos \left(\frac{2(S_n)}{I_{n,0}} - 1 \right) \quad (12)$$

Solving equation (8) when $V_n=0$ is useful because at this specific point, the response is dependent on the relative phase Δ_n , but not on the applied voltage fraction α_n . However, this implies that the right time instant (sample) must be determined when $V_n=0$.

The procedure to find this time instant when $V_n=0$ is summarized next: First, the returning points R1 and R2 of the applied voltage are located (as illustrated in Fig. 8) under the assumption that the excitation signal is purely AC (i.e., mean value=0). This is a reasonable assumption under normal operating conditions; whenever the assumption does not hold, computation of Δ_n is temporarily disabled. DC components in the applied voltage can be detected by computing the mean value of the reconstructed voltage V over one or several periods.

An easy way to locate R1 and R2 is to scan the response signal for two successive extrema which are equal to neither 0.5 nor -0.5. However, this does not work for certain values of input signal amplitudes. For example with 225 kV applied voltage as in Fig. 8, one signal extremum is located exactly at -0.5.

Therefore, a method based on zeros crossings is used instead (Fig. 8, bottom). First, all zero crossings in a given signal section (e.g. 1.25 rated voltage periods) are located. Then, for each zero crossing, the sum

S_i of the three time intervals defined by four (or any even number greater than four) consecutive zero crossings is computed (see the framed example in Fig. 8, bottom: the vertical dotted lines correspond to zero crossings of the base signal S_1):

$$S_i = \sum_{k=i}^{i+3} (t_{Zk+1} - t_{Zk}) \quad (13)$$

The zero crossings that lead to the largest sum S_i then contain in their middle the points R1 and R2. The time instant when $V_n=0$ is finally located in the center between R1 and R2.

An alternative method to locate the returning points R1 and R2 is to use the zero crossings count output k . The returning points R1 and R2 are located on the extrema (either minimum or maximum, determined, e.g., by second derivative) of the measured signal (base or quadrature) that are located within the time period where the counter output k is maximal or minimal. These extrema of k indicate the returning points of the applied voltage V , since k is an approximation of V .

Measurement of small voltages

The invention also provides a mechanism for determining the applied voltage V between the terminals 1a and 1b in cases where the voltage V is much smaller than the rated voltage and the electro-optic phase shift is therefore within $\pm 180^\circ$. Specifically, the measurement of voltages that lead to phase shifts smaller than or within $\pm 180^\circ$ is identical to large voltages (as described above), but with two differences:

- No signal normalization. Phase shifts smaller than or within $\pm 180^\circ$ lead to signals that do not cover the entire possible output amplitude range. I.e., the intensity I of the light beam exiting the electro-optical light transmitting element 2a, 2b, ... as given by equation (1) does not cover the entire admissible range [0;

$I_{n,0}$]. Therefore, signal normalization must be disabled in order to preserve the correct information about signal amplitude, and thus about the applied voltage.

- No measurement of Δ . Since the estimation of Δ_n , and thus of the temperature, relies on zero-crossings in the response signal, this cannot be performed when the electro-optic phase shift is within $\pm 180^\circ$.

To detect voltages V with phase shift below or within $\pm 180^\circ$, one cannot rely on the voltage measurement itself, because this is obviously only available after signal normalization has been done. Instead, one relies on the scale and offset factors produced by the normalization procedure in equations (5)-(6). In fact, in a first time period $[t_1; t_2]$ with $t_2 > t_1$ the phase shift must be above or outside $\pm 180^\circ$ (i.e. full output amplitude range covered, "large" range of voltages applied to the terminals 1a and 1b). Then, scale and offset remain approximately constant. When in a second time period $[t_3; t_4]$ (with $t_4 > t_3$), the phase shift drops below or within $\pm 180^\circ$, at least one of these factors would change rapidly (i.e., within one period of the voltage V), because the signal S_n needs to be rescaled.

Therefore, the voltage V or V_n is considered "small" (phase shift $< \pm 180^\circ$) when either

$$scale(t) - scale(t - \Delta) > \delta_{scale} \quad (14) \text{ or}$$

$$offset(t) - offset(t - \Delta) > \delta_{offset} \quad (15)$$

Here, δ_{scale} and δ_{offset} are threshold values that are used to detect significant or rapid changes in the corresponding parameters. Δ is the time interval that separates two consecutive evaluations of scale and/or offset. (Note: time interval Δ does not refer to a phase shift here!). For proper operation of the method, this time interval Δ must be small enough to ensure proper reaction time (no slowly changing voltages), but larger

than one signal period (i.e. 20 ms at 50 Hz or 16.6 ms at 60 Hz).

Notes:

Figs. 2a - 2c show arrangements where the
5 electro-optical light transmitting elements 2, 2a, 2b are
operated in reflection mode using a reflector 28, i.e.
the light passes the optical sensor 21 twice. Alterna-
tively, the electro-optical light transmitting element 2
may also be operated in transmission mode as in Fig. 1,
10 i.e. the light passes the crystal 21 only once.

Another option to remove the ambiguity in-
stead of or additionally to using a quadrature signal is
to operate the sensor with light of two different wave-
lengths.

15 The embodiments described here refer to two
or three electro-optical light transmitting elements. It
should be noted, however, that the method and/or device
according to the invention is or are suitable for any
number of electro-optical light transmitting elements
20 greater than two and/or more than two measured signals.
The measured signal from any electro-optical light trans-
mitting element can be used to disambiguate the signal(s)
from any other electro-optical light-transmitting ele-
ment(s), in particular if at least one measured signal is
25 phase-shifted with respect to the other measured sig-
nal(s) (e.g. one element has a phase shifting element,
the other one(s) not).

The role of "base" and "quadrature" signals
in this invention is interchangeable, i.e. the quadrature
30 signal can be used to resolve ambiguities in the deriva-
tion of the voltage from the base signal, and/or the base
signal can be used to resolve ambiguities in the deriva-
tion of the voltage from the quadrature signal.

It should be noted that the described hypoth-
35 eses-method in the "Measurement of the applied voltage"-
section is in principle also suitable for disambiguating
a "base" signal with a "quadrature" signal in a sensor in

which both signals originate from the same electro-optical light-transmitting element, e.g. a classical sensor in which two channels (one without and one with a quarter-wave retarder) are read out from the same electro-optical light-transmitting element.

Reference numbers

10	1a, 1b:	terminals
	2, 2a, 2b, 2c:	electro-optical light transmitting element (sensor module)
	3:	phase shifting element
	4:	light processing module
15	4a, 4b, 4d:	photodetector
	4c:	light source
	21:	optical sensor, e.g. electro-optic crystal
	22:	first polarizer
20	23:	second polarizer
	24:	beam splitter
	25:	deflection prism
	26:	coupling lens
	27:	optical fiber
25	28:	reflector
	41:	control unit
	41a:	central processing unit (CPU)
	41b:	memory
	S ₁ , S ₂ , S ₃ , S _n :	signals
30	V:	voltage
	I:	intensity

Claims

1. A method for measuring a voltage (V) between a first (1a) and second terminal (1b), wherein the
5 first terminal (1a) is spatially separated from the second terminal (1b) and wherein the voltage (V) creates an electric field between the terminals (1a, 1b), the method comprising the steps of

arranging at least a first and a second electro-optical light transmitting element (2, 2a, 2b) in the
10 electric field between the first (1a) and the second terminal (1b),

passing light through the first and the second electro-optical light transmitting element (2a, 2b),

15 measuring at least a first signal (S₁) from the first electro-optical light transmitting element (2a) and at least a second signal (S₂) from the second electro-optical light transmitting element (2b), wherein the first signal (S₁) is indicative of the electric field
20 over the first electro-optical light transmitting element (2a), wherein the second signal (S₂) is indicative of the electric field over the second electro-optical light transmitting element (2b), and wherein the signals (S₁, S₂) are periodic functions of the voltage (V),

25 deriving the voltage (V) from the first (S₁) and the second signal (S₂),

wherein the second signal (S₂) is used to resolve an ambiguity in the deriving of the voltage (V) using the first signal (S₁),

30 characterized in that the electro-optical light transmitting elements (2a, 2b) are arranged electrically in series.

2. The method of claim 1, wherein the light
35 transmitting elements (2a, 2b) are arranged in series for distributing the electric field over the electro-optical light transmitting elements (2a, 2b), and/or the light

transmitting elements (2a, 2b) are arranged in series in an axial direction between the terminals (1a, 1b).

3. The method of any of the preceding claims,
5 wherein a waveform of the applied voltage (V) between the first terminal (1a) and the second terminal (1b) is reconstructed using a plurality of the electro-optical light transmitting elements (2a, 2b) without requiring a quadrature signal for each electro-optical light trans-
10 mitting element (2a, 2b).

4. The method of any of the preceding claims,
wherein the first electro-optical light transmitting element (2a) is operated without a retarder.

15

5. The method of any of the preceding claims,
wherein during the derivation, ambiguities in a single signal or, in the case of more than two signals, in a subset of signals of the at least one first signal (S_1)
20 and at least one second signal (S_2) are resolved by one of the signals being phase-shifted with respect to the other signals.

6. The method of any of the preceding claims,
25 wherein the first signal (S_1) and the second signal (S_2) have the same periodicity of the voltage (V) or wherein the first signal (S_1) is scaled to the second signal (S_2) such that they have the same periodicity of the voltage (V) and wherein the first signal (S_1) and the second signal (S_2) have a mutual phase shift other than zero.
30

7. The method of any of the claims 5-6,
wherein the phase shift between the first signal (S_1) and the second signal (S_2) is at least partly introduced by a
35 phase shifting element (3) that is arranged in an optical path in the second electro-optical light transmitting el-

ement (2b), and in particular wherein the phase shifting element (3) is a $\lambda/4$ retarder.

8. The method of any of the claims 5-7,
5 wherein the phase shift between the first signal (S_1) and the second signal (S_2) is a function of temperature of the phase shifting element (3) and the temperature of the phase shifting element (3) is derived from the second signal (S_2).

10 9. The method of any of the preceding claims, wherein the first signal (S_1) and the second signal (S_2) are based on an electric field-dependent change of a physical property of the light that is passed through the
15 first and second electro-optical light transmitting elements (2a, 2b) by means of the electro-optical light transmitting elements (2a, 2b).

10 10. The method of claims 8 and 9, wherein the electric field-dependent change is a function of the temperature of the electro-optical light transmitting element (2, 2a, 2b) and wherein the derived temperature of the phase shifting element (3) is used in deriving the voltage (V).

25 11. The method of any of the preceding claims, wherein the voltage is in the high-voltage range, and/or the voltage is an AC-voltage.

30 12. The method of any of the preceding claims, wherein in a first time interval $[t_1; t_2]$ between a first time t_1 and a second time $t_2 > t_1$ a range of the voltages (V) over the terminals (1a, 1b) is large enough for the signals (S_n) to reach their maximum and minimum
35 values as functions of the voltages (V) and

wherein in a second time interval $[t_3; t_4]$ between a third time $t_3 > t_2$ and a fourth time $t_4 > t_3$ the

range of the voltages (V) is not large enough for the signals (S_n) to reach their maximum and minimum values as functions of the voltages (V) and

wherein at least a scale and/or an offset of
5 the signals (S_n) that was or were derived in the first time interval [t1; t2] is or are used in deriving the voltage (V) in the second time interval [t3; t4].

13. The method of any of the preceding
10 claims, wherein the electro-optical light transmitting element (2, 2a, 2b) comprises an optical sensor (21) introducing a field-dependent phase shift between a first polarization or mode and a second polarization or mode of light passing through the electro-optical light transmit-
15 ting element (2, 2a, 2b), and in particular wherein the optical sensor (21) comprises

an electro-optical device with field-dependent birefringence, in particular a crystal, in particular of crystalline $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) or $\text{Bi}_4\text{Si}_3\text{O}_{12}$
20 (BSO),

or a poled waveguide exhibiting a Pockels effect,

or a piezo-electric device, in particular of crystalline quartz or a piezoelectric ceramic, and a
25 waveguide carrying at least two modes, wherein the waveguide is connected to the piezo-electric device thus that a length of the waveguide is field-dependent.

14. The method of any of the preceding
30 claims, wherein only one signal (S_n) per electro-optical light transmitting element (2, 2a, 2b) is measured.

15. The method of any of the preceding claims, comprising:

35 applying to each electro-optical light transmitting element (2a, 2b) a partial voltage (V_n),

determining from the first and second signals (S1, S2) the partial voltage (Vn) for each electro-optical light transmitting element (2a, 2b), and

determining the total voltage (V) between the first terminal (1a) and the second terminal (1b) by calculating the sum ($V = \sum V_n$) of all partial voltages (Vn).

16. The method of any of the preceding claims, further comprising the steps of:

defining at least one internal parameter $\alpha_n = V_n/V$, wherein V_n = partial voltage applied to the nth electro-optic light transmitting element (2a, 2b) and V = total voltage between the first terminal (1a) and the second terminal (1b),

determining an estimate of α_n for all electro-optical light transmitting elements (2a, 2b), and

using the α_n for resolving the ambiguity in the deriving of the voltage (V) from the first signal (S1).

20

17. The method of claim 16, further comprising the steps of:

measuring electrical signals S_n as a function of the intensities of the light beam exiting each electro-optical light transmitting element (2a, 2b),

determining all partial voltages V_n according to

$$V_n = \frac{V_{h,n}}{\pi} \left(\left(\pm \arccos \left(\frac{2(S_n - b_n)}{G_n \cdot I_{n,0}} - 1 \right) + K \cdot 2\pi \right) - 2\pi \Delta_n \right)$$

with $V_{h,n}$ = half-wave voltage of the crystal (21) in the nth electro-optic light transmitting element (2a, 2b), b_n = signal offset, G_n = cumulated gain of all components in the measurement chain from photodiode to amplifier, $I_{n,0}$ = intensity of the exiting beam with zero retardation, K = count of periods of the cosinusoidal re-

sponse, and Δ_n = relative phase of the signal with respect to the voltage (V , V_n), and

using the α_n for disambiguating the sign of the arccosine.

5

18. The method of any of the preceding claims, wherein the resolving of the ambiguity comprises a step of taking a binary decision between two hypotheses (h^+ , h^-), wherein the hypotheses (h^+ , h^-) correspond to different possible voltage values ($V_1^{h^-}$, $V_1^{h^+}$) for a given value of the first signal (S_1), and

wherein the step of taking a binary decision comprises a derivation of an expected value ($S_2^{h^+}$, $S_2^{h^-}$) of the second signal (S_2) for each of the hypotheses (h^+ , h^-) and a comparison of the expected value ($S_2^{h^+}$, $S_2^{h^-}$) to a measured value of the second signal (S_2).

19. The method of claim 17 and 18, wherein the step of taking a binary decision comprises using the α_n to compute V_n and V , and selecting that expected value ($S_2^{h^+}$, $S_2^{h^-}$) of the second signal (S_2) which is closer to the measured value of the second signal (S_2).

20. The method of claim 19, wherein strongly erroneous α_n are detected from an incorrect hypotheses selection, in particular from a discontinuity in the measured voltage (V), and the most common values of α_n which are used most of the time are determined to be the correct α_n .

30

21. The method of any of the preceding claims 16-20, further comprising the step of recursively deriving at least one of the internal parameters (α_n) by:

initializing an auxiliary control loop with the estimate of α_n for all optical channels, wherein the internal parameter (α_n) is descriptive of a distribution

35

of the voltage (V) over the electro-optical light transmitting elements (2a, 2b),

taking a first series of measurements, and
based on the resulting V_n , calculating more
5 exact α_n using equation $\alpha_n = V_n/V$ and the most common values of α_n .

22. The method of claim 21, further comprising the steps of:

10 using the more exact α_n as new estimated of α_n , and

converging the α_n , and/or tracking a time dependence $\alpha_n(t)$ of the α_n .

15 23. The method of any of the preceding claims, further comprising the steps of

arranging at least a third electro-optical light transmitting element (2c) in the electric field between the first (1a) and the second terminal (1b),

20 passing light through the third electro-optical light transmitting element (2c),

measuring at least a third signal (S_3) from the third electro-optical light transmitting element (2c) wherein the third signal (S_3) is indicative of the electric field over the third electro-optical light transmitting element (2c), and wherein the third signal (S_3) is a
25 periodic function of the voltage (V),

deriving the voltage (V) from the first signal (S_1), the second signal (S_2), and the third signal
30 (S_3), wherein the second signal (S_2) is used to resolve an ambiguity in the deriving of the voltage (V) using the first (S_1) and the third signal (S_3).

24. The method of any of the preceding
35 claims, wherein during the derivation, the ambiguity is removed instead of or additionally to using a quadrature signal by using light of two different wavelengths.

25. The method of any of the preceding claims, wherein the electro-optical light transmitting elements (2a, 2b) are optically read out in parallel.

5 26. A device for measuring the voltage (V) comprising means for carrying out the steps of the method according to any of the preceding claims.

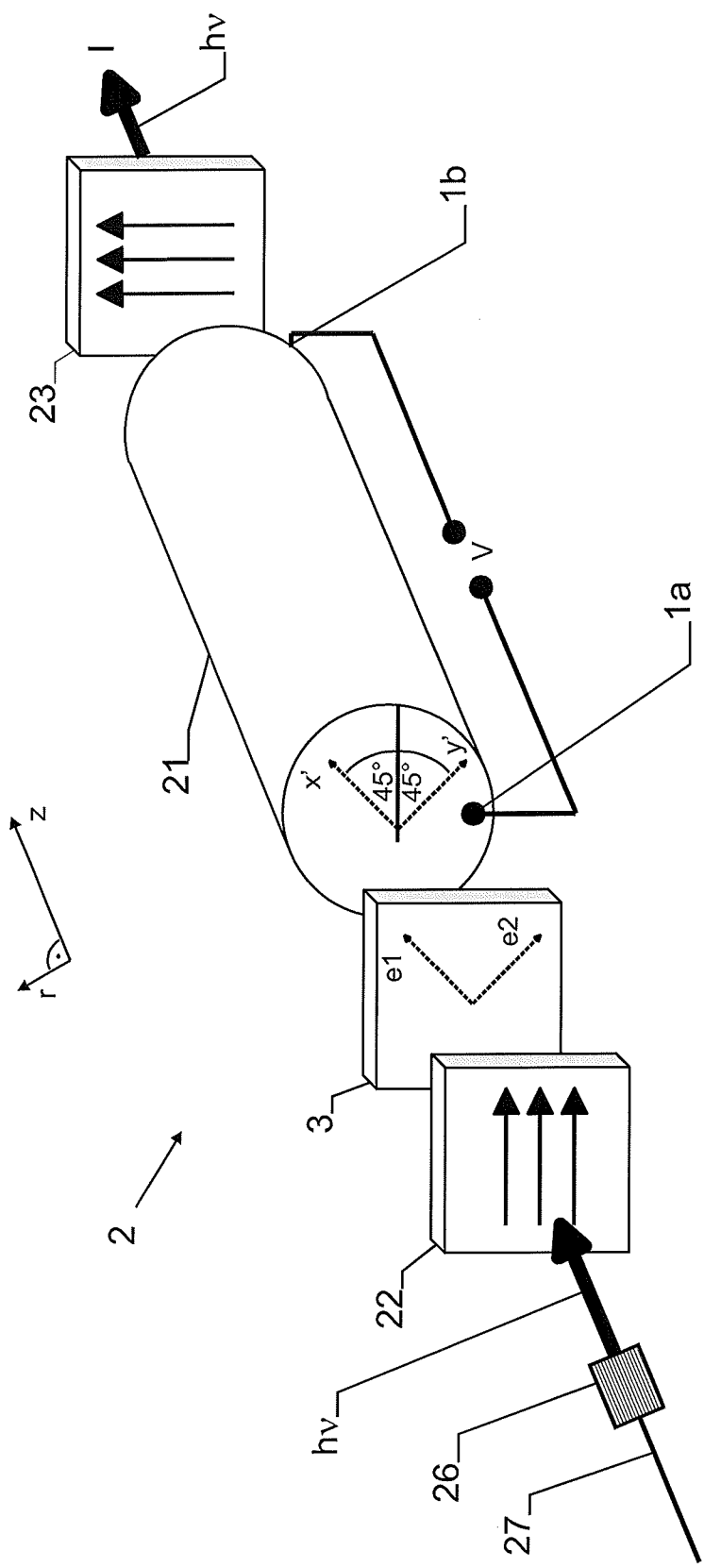


Fig. 1

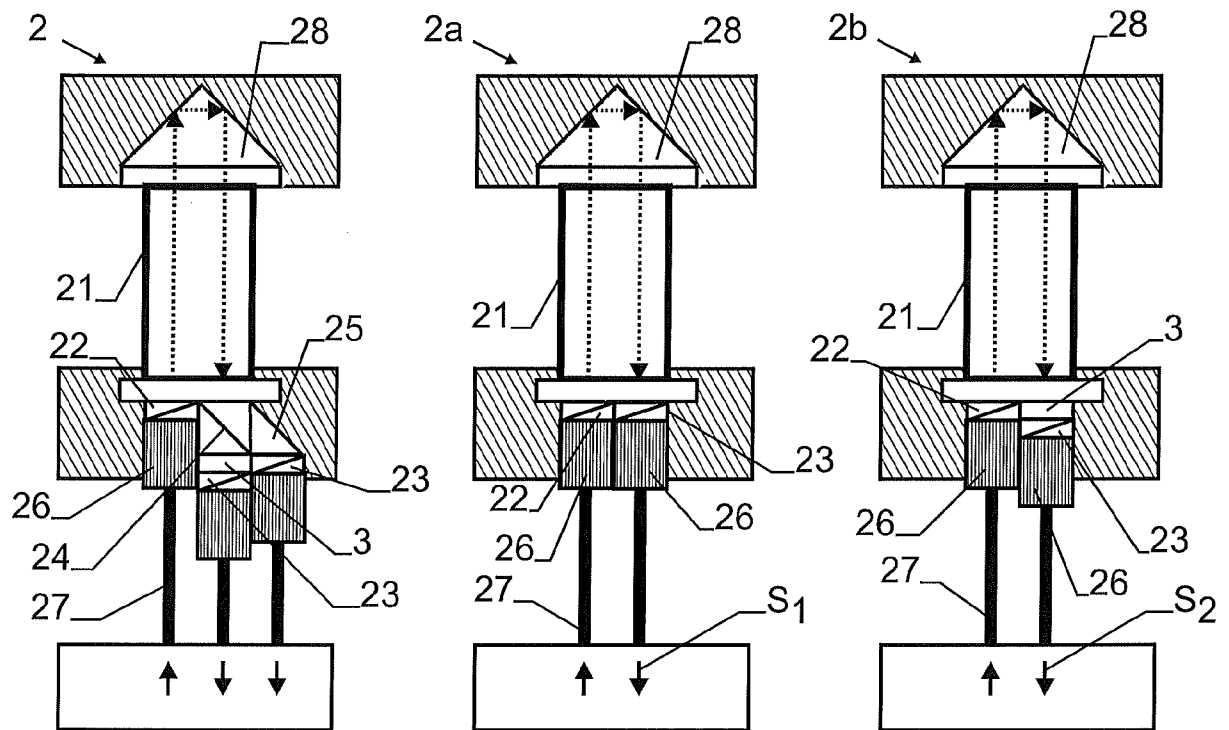


Fig. 2a

Fig. 2b

Fig. 2c

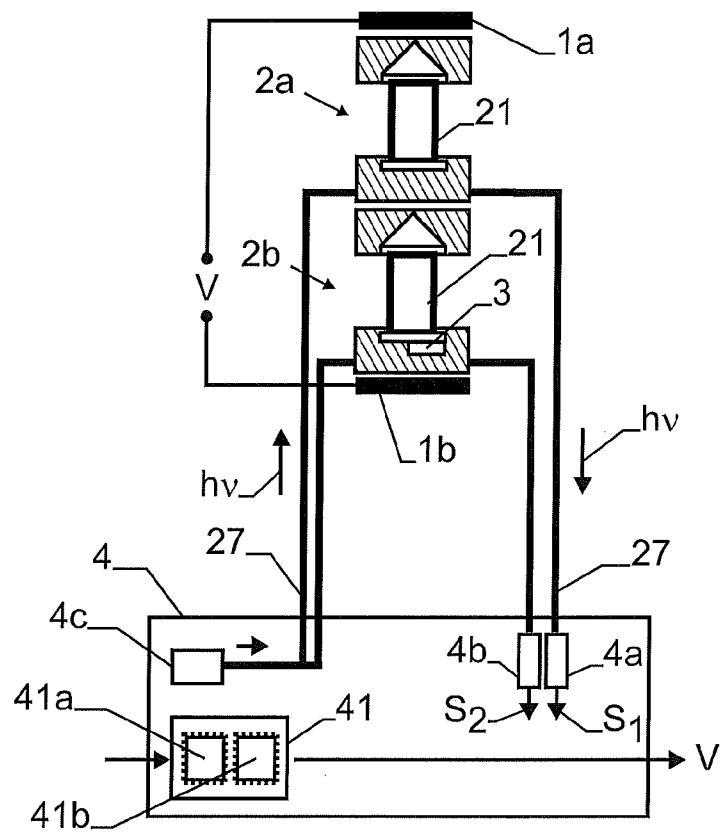


Fig. 3

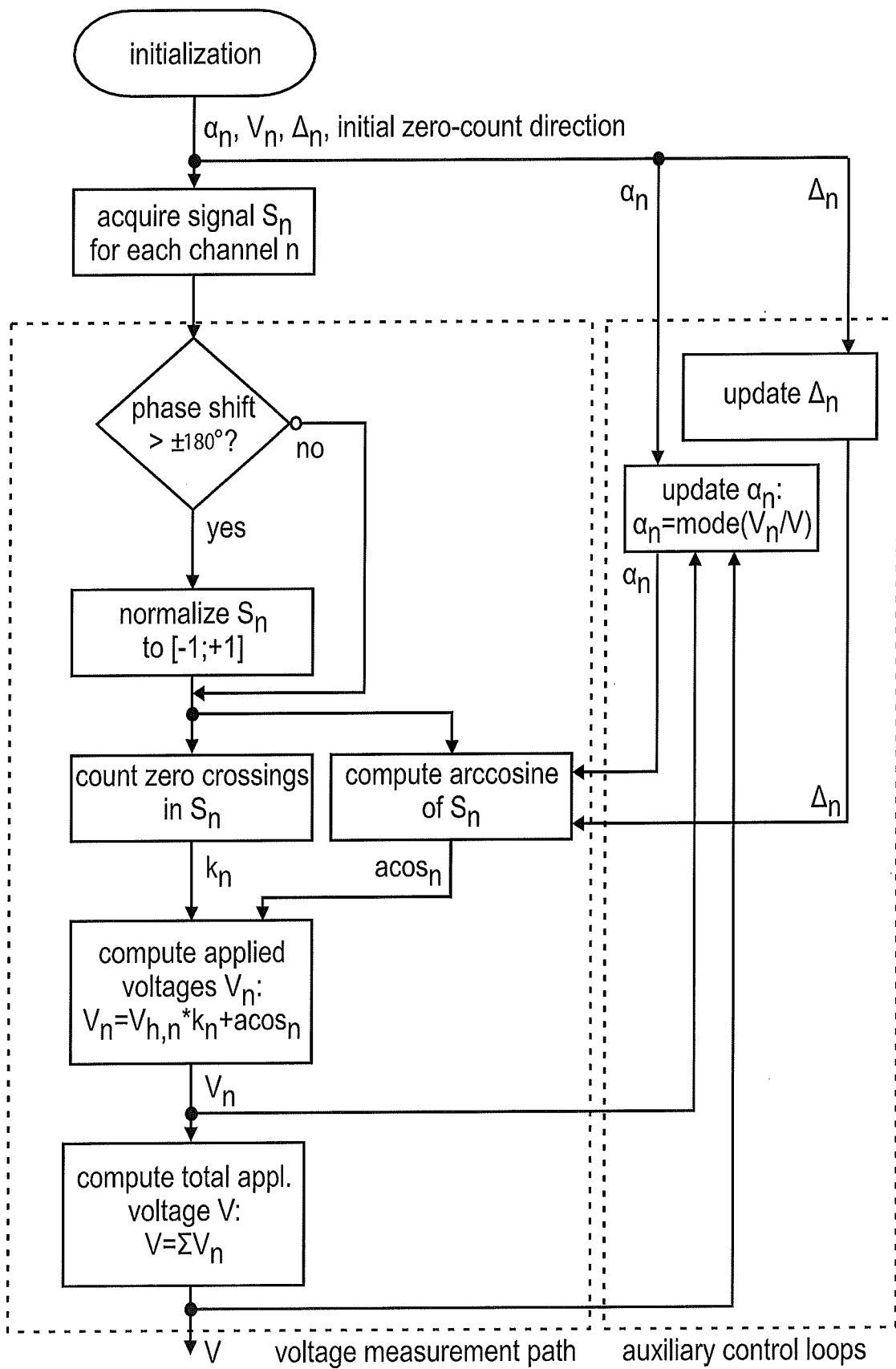


Fig. 4

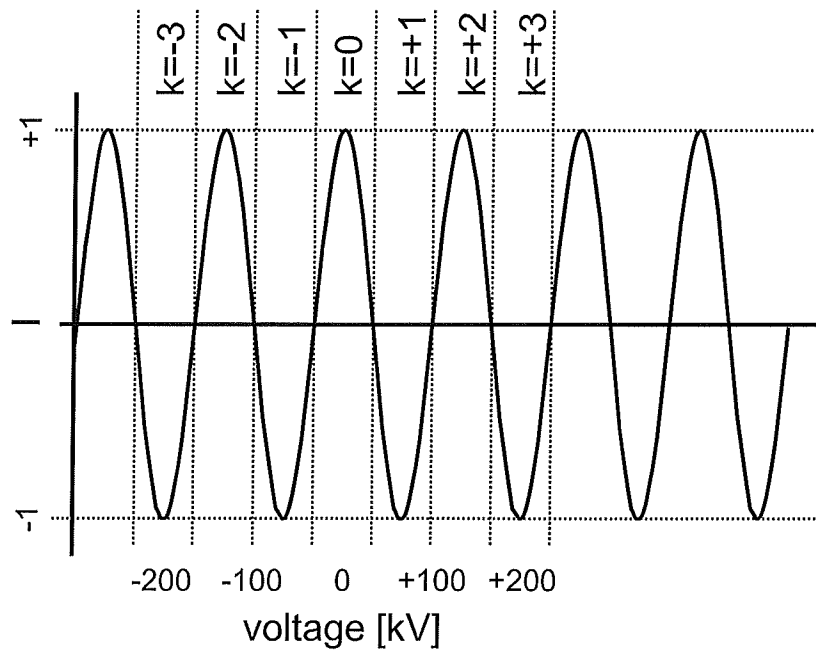


Fig. 5

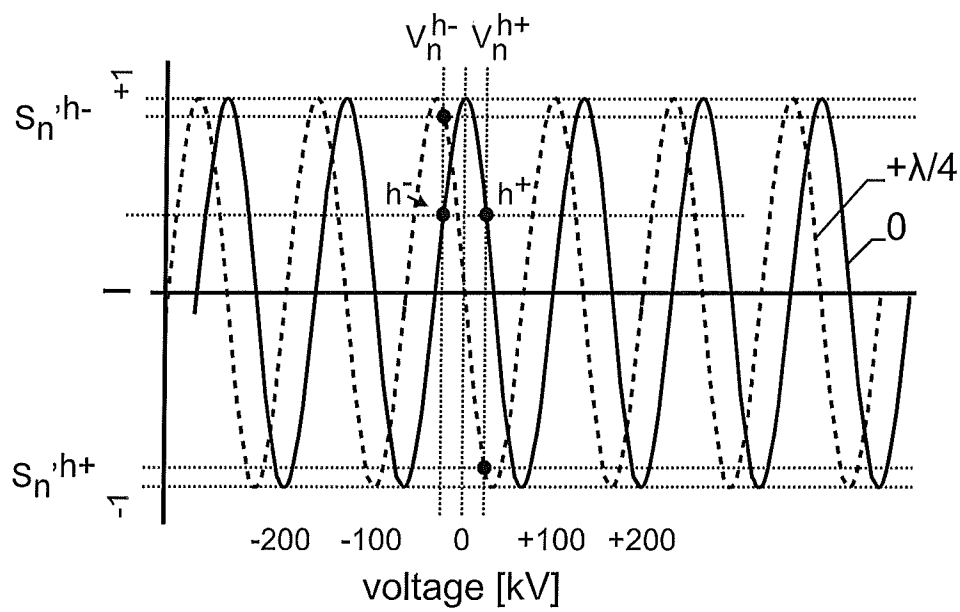


Fig. 6

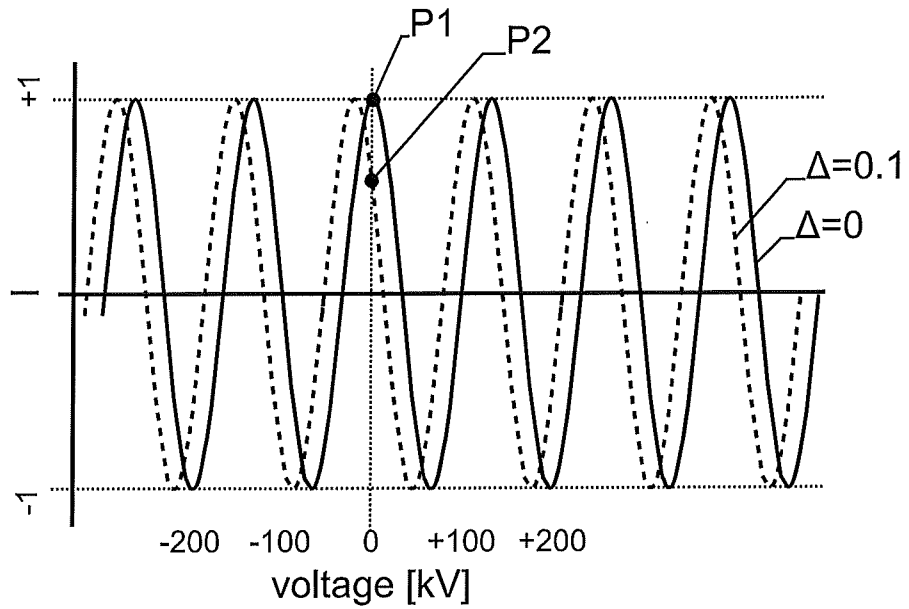


Fig. 7

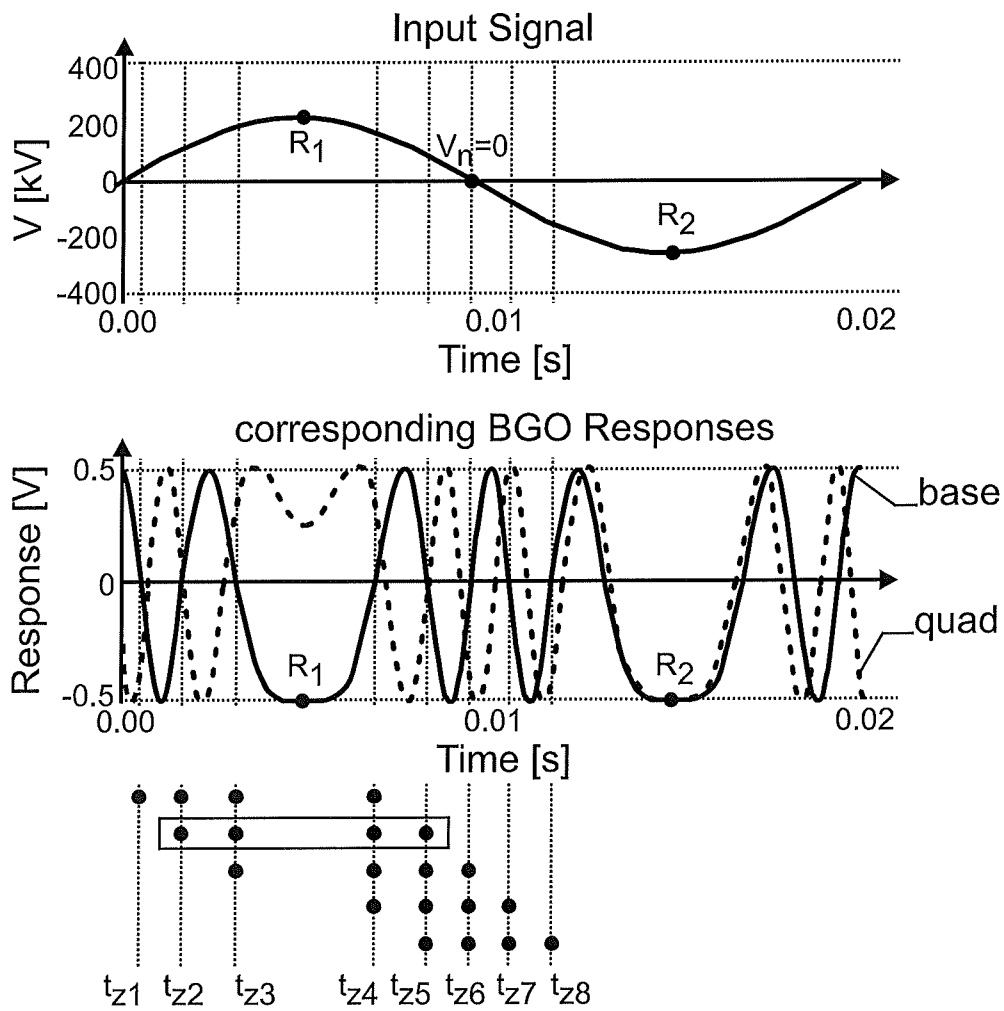


Fig. 8

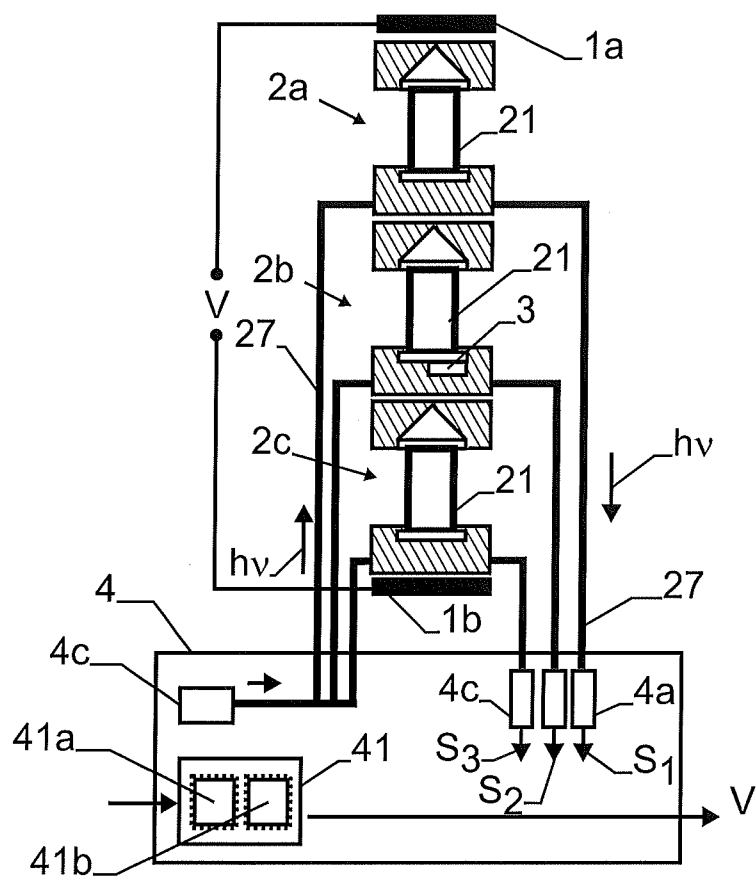


Fig. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/060064

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R15/24
ADD.

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)
G01R

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P L Y	WO 2011/154029 A1 (ABB RESEARCH LTD [CH]; WILDERMUTH STEPHAN [CH]; BOHNERT KLAUS [CH]; KO) 15 December 2011 (2011-12-15) page 1, line 5 - page 3, line 23; figures 1,2b,2c,4,10 page 11, line 20 - line 26 page 20, line 13 - page 26, line 4 ----- US 6 252 388 B1 (JAEGER NICOLAS AUGUST FLEMING [CA] ET AL) 26 June 2001 (2001-06-26) abstract; figures 1,2 ----- -/-	1-11, 13-15, 23-26 1-26



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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

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

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

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INTERNATIONAL SEARCH REPORT

International application No
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