



(51) **International Patent Classification:**
G01M 11/00 (2006.01) **G01J 9/02** (2006.01)
G01D 5/353 (2006.01)

(21) **International Application Number:**
PCT/NL2011/050238

(22) **International Filing Date:**
11 April 2011 (11.04.2011)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
10159506.4 9 April 2010 (09.04.2010) EP

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(81) **Designated States (unless otherwise indicated, for every
kind of national protection available):** AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP,
KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD,
ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI,
NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD,
SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States (unless otherwise indicated, for every
kind of regional protection available):** ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG,
ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) **Title:** SCANNING WAVELENGTH SYSTEM AND METHOD CALIBRATING SUCH A SYSTEM

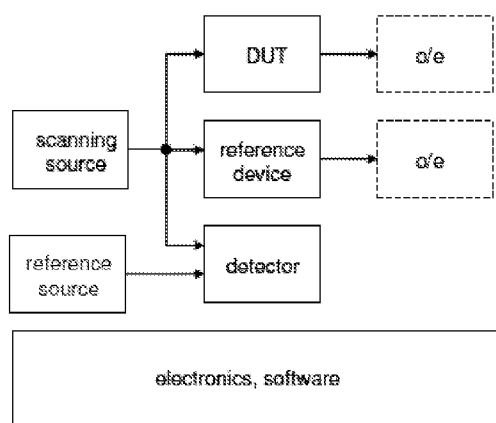


Figure 8

(57) **Abstract:** A scanning wavelength system measures properties of a device under test, during a scan wherein the wavelength of an optical probe signal are varied. During the scan the scanning wavelength system is characterized or calibrated by - supplying a first fraction of the optical probe signal to a device under test; - supplying a second fraction of the optical probe signal to a reference device; - supplying a third fraction of the optical probe signal to detector; - supplying light at a reference wavelength from a reference source to the detector together with the third fraction; - processing a detector signal by electronics and/or software to identify an event that a wavelength of the scanning source substantially equals the reference wavelength.

Title: Scanning wavelength system and method calibrating such a system

Field of the invention

The invention relates to a scanning wavelength optical system and a wavelength tracking and reference unit for such a system..

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Background

Figure 1 shows a known setup for characterizing or calibrating the wavelength response an optical system (DUT) by means of a narrow-band scanning source. Examples of optical systems are spectrometers, assemblies of lenses, mirrors, prisms, gratings, etc., but also single optical components such as Fiber Bragg Gratings can be considered as optical systems. Examples of scanning sources are tunable lasers, and broadband sources with a tunable filter. A broadband source is for example a (superluminescent) LED, or an Amplified Spontaneous Emission (ASE) source. A tunable filter is for example a Fabry Perot filter, the cavity length of which is controlled by means of a piezo-electric device. The set up of this figure and the other figures is connected to electronics, but the connections to the electronics have been omitted for the sake of clarity.

20 Figure 2a-c show data for characterization by means of a scanning source. The scanning source provides an optical probe signal, the wavelength of which is scanned from λ_1 to λ_2 over a timeframe $t_1 - t_2$ (Figure 2a). During the scan, the response of a Device Under Test (DUT) is measured as a function of time (Figure 2b). The DUT can be any optical system as previously mentioned. The relation $\lambda(t)$ is known to a certain accuracy from the design or calibration of the system, and we can obtain the response of the DUT as a function of wavelength (Figure 2c). The DUT may be reflective or transmissive, for example a Fabry Perot filter or FBG may be characterized by means of its reflection, or by means of its transmission. The DUT may have an optical

output that needs to be converted to an electrical signal by means of an optical-electrical (o/e) converter, as is the case if the DUT is an assembly of optical components such as lenses, mirrors, prisms and/or gratings. An o/e converter is for example a photodiode. Alternatively, the DUT may provide an electrical
5 signal by itself, for example if the DUT is a photodiode with unknown wavelength dependent response, or if it is a system with a built-in o/e converter.

Figure 3 shows a set up with an added wavelength reference. For accurate results, the wavelength of the source has to be accurately known
10 throughout the scan. To improve the wavelength accuracy, a fraction of the probe signal is applied to a reference device of which the wavelength response is accurately known. The response of this reference device to the scanning wavelength provides accurate information on the wavelength during the scan. The reference device can be implemented as a wavelength filter, an
15 interferometer, or any other suitable device. In particular the use of an interferometer with a periodic wavelength response enables high accuracy, since the wavelength period can be chosen (much) smaller than the actual scan range. The wavelength is obtained by counting interferometer fringes (periods), and from interpolation within fringes. Even more particular, the
20 devices as described in EP1549904B1 and WO2004033987A are attractive options.

Figure 4 shows a further improved set-up with an absolute wavelength reference. Figure 5 shows wavelength vs. time. During the wavelength scan, a signal is provided at $t=t_{ref}$, indicating the event that the
25 scan wavelength equals the reference wavelength. This improves the absolute wavelength accuracy, as well as robustness against hysteresis and drift. It is known that the wavelength of the scanning source is equal to the reference wavelength at the time point t indicated by the signal. This may be used to select one of a plurality of possible assignments of wavelengths to successive
30 periods of the periodic wavelength response of the reference device, the

assignment being selected that is consistent with the scanning source having the reference wavelength at the time of the event. Similarly, it may be used to apply a time shift to the known relation $\lambda(t)$ of the wavelength of the scanning source as a function of time, a time shift value being selected that is
5 consistent with the scanning source having the reference wavelength at the time of the event.

An attractive option for an absolute wavelength reference is the Fiber Bragg Grating (FBG), as described in WO 98/17969, US 005838437A, US 006115122A, US 005892582A, US006327036B1 and US006449047B1. An
10 alternative approach using two non-equal interferometers is described in US20040091002A1 and US006498800B1.

Problem(s) of the Art

15 The absolute system accuracy is determined by the accuracy of the absolute reference. In state of the art systems, an FBG is applied as absolute reference. The Full Width Half Max (FWHM) of the FBG is typically 50 pm or more, which limits the absolute accuracy of the FBG reflection wavelength to the order of a pm.

20 Therefore, also the absolute system accuracy in the order of a pm. This is not always sufficient, for example if the DUT is a sensor based on a ring resonator or Fabry Perot resonator, and is meant to be interrogated at sub-pm level.

25 Summary

Among others, a method of characterizing or calibrating a scanning wavelength system and a system that uses such a method that provides for high accuracy.

A method of characterizing or calibrating a scanning wavelength system is provided that comprises

- scanning a wavelength of an optical probe signal from a scanning source;
- supplying a first fraction of the optical probe signal to a device under test;
- 5 - supplying a second fraction of the optical probe signal to a reference device;
- supplying a third fraction of the optical probe signal to detector;
- supplying light at a reference wavelength from a reference source to the detector together with the third fraction or to a further detector;
- processing a detector signal by electronics and/or software to identify an
- 10 event that a wavelength of the scanning source substantially equals the reference wavelength.

This makes it possible to monitor relative drift. In an embodiment the method comprises

- supplying light from a further reference source to the said reference element
- 15 together with said fraction of light from the reference source;
- monitoring a drift of the reference element with the light from the further reference source;
- determining a relative drift of the reference source with respect to the reference element;
- 20 - determining drift of the reference source based on the drift of the reference element and the relative drift of the reference source with respect to the reference element. In an embodiment a fraction of light is supplied from the reference source to a reference element which is said reference device or a further reference device. If only a single reference element is used, a reference
- 25 fraction of the optical probe signal, which is the second fraction or a further fraction may be supplied to the reference source together with the light from the further reference source.

A scanning wavelength system is provided that comprises

- a scanning source configured to scan a wavelength of an optical probe signal
- 30 from the scanning source

- a reference source;
- a reference device configured to receive a fraction of the optical probe signal, and, in an improved embodiment, light from the reference source;
- a detector configured to receive a further fraction of the optical probe signal, and further light from the reference source;
- electronics and/or software configured to process a detector signal from said detector to identify an event that a wavelength of the scanning source substantially equals the reference wavelength.

10

Brief description of the drawing

These and other aspects will become apparent from a description of embodiments, using the following figures

- 15 Figure 1 shows a known setup for characterizing or calibrating the wavelength response an optical system
- Figure 2a-c show data for characterization by means of a scanning source
- Figure 3 shows a set up with an added wavelength reference
- Figure 4 shows an improved set-up with an absolute wavelength reference
- 20 Figure 5 shows wavelength vs. time
- Figure 6 shows a set-up for using input from a reference source and a scanning source
- Figure 7 shows in- and output signals
- Figure 8 shows a basic embodiment.
- 25 Figures 9 and 10 show improved embodiments for monitoring relative and absolute drift.

Description of embodiments

The invention is used in a setup for characterizing or calibrating the wavelength response an optical system (DUT) by means of a narrow-band scanning source. The scanning source provides an optical probe signal, the wavelength of which is scanned from λ_1 to λ_2 over a timeframe $t_1 - t_2$ (Figure 5 2a). During the scan, the response of a Device Under Test (DUT) is measured as a function of time (Figure 2b). A response of the DUT as a function of wavelength is obtained (Figure 2c). An optical-electrical (o/e) converter may be provided to convert an optical output of the DUT to an electrical signal. The o/e converter may for example be a photodiode. Alternatively, the DUT may 10 provide an electrical signal by itself.

In addition to the DUT, an added wavelength reference is used. A fraction of the probe signal is applied to a reference device that has a known response as a function of wavelength. The response of this reference device to the scanning wavelength provides accurate information on the wavelength 15 during the scan.

In an embodiment the reference device is a wavelength filter, an interferometer, or any other suitable device. In particular the use of an interferometer with a periodic wavelength response enables high accuracy, since the wavelength period can be chosen (much) smaller than the actual scan 20 range. The wavelength is obtained by counting interferometer fringes (periods), and from interpolation within fringes. Even more particular, the devices as described in EP1549904B1 and WO2004033987A are attractive options.

An absolute wavelength reference is used to provide an indication of 25 a time point of the event that the scan wavelength equals the reference wavelength. This signal is used to improve the absolute wavelength accuracy, and/or to compensate hysteresis and drift as in the prior art. But instead of the filters used as absolute wavelength reference in the prior art, a reference source is used that supplies light at an accurately defined wavelength.

Figure 6 shows a set-up for using input from a reference source and a scanning source. The proposed method is based on the use of a reference laser rather than a reference FBG. The linewidth of the reference laser is much narrower than the FWHM of the FBG reflection peak. Fractions of the scanning source and reference source outputs are both incident on a single detector, thereby creating an electrical signal with a beat frequency equal to the difference in optical frequencies.

Figure 7 shows in- and output signals of the set-up: reference and scan inputs (a) and resulting electrical spectrum of the detector signal (b) with the spectrum for $\lambda_{\text{ref}} = \lambda_{\text{scan}}$ shown as a dashed curve. For small $d\lambda$, the beat frequency is given by:

$$f = \frac{c}{\lambda^2} d\lambda \quad \text{with } d\lambda = |\lambda_{\text{scan}} - \lambda_{\text{ref}}|$$

As an indication, for $d\lambda = 1$ pm and $\lambda \approx 1550$ nm, the beat frequency is 125 MHz, i.e. a frequency that can be processed electrically. The detector response is analyzed, for example by means of electronics and/or software. The beat frequency is minimum if the scan wavelength equals the reference wavelength (a narrow spectrum remains due to the finite linewidth of the two optical spectra). The system in Figure 6 generates a signal if this event occurs, thereby providing an absolute wavelength reference. The system accuracy is determined by the accuracy of the reference source wavelength, which is much better than achievable with FBGs. A suitable reference source is for example a Distributed Feed Back laser (DFB laser).

Further improvement of the accuracy can be achieved by monitoring the reference source by the same (or an additional representative) reference device, to monitor drift of the reference source relative to the reference device(s). Even further improvement of the accuracy is achieved by monitoring the reference device(s) by another ultra-stable reference source, such as a source based on a gas emission line, or the like. The wavelength of this ultra-

stable reference is not necessarily inside or even close to the wavelength scan range. This approach allows transformation of the absolute accuracy of an ultra-stable source to the wavelength range of interest.

The development provides an accurate absolute wavelength reference for use in wavelength-scanning interrogation / characterization systems. In particular, this development improves the accuracy and sensitivity for sensor systems in which a wavelength-scanning source is applied to detect the wavelength shift of sensors which are based on ring resonators or Fabry Perot resonators.

Figure 8 shows a basic embodiment. The output of the scanning source is split in three fractions (at any suitable split ratio):

1. A fraction that characterizes the Device Under Test
2. A fraction that measures the wavelength of the scanning source by means of a suitable reference device. In practice this reference device is thermally and vibrationally isolated to improve accuracy.
3. A fraction that is incident on a detector, on which also the reference source is incident. The detector signal is processed by electronics and / or software to identify the event that the scan wavelength equals the reference wavelength.

Figure 9 shows an improved embodiment for monitoring relative drift between a reference source and reference devices. As compared to the situation in Figure 8, the reference source is split in two fractions

1. A fraction that is incident on the detector on which also the scanning source is incident.
2. A fraction that is monitored by a reference device. This may be the same reference device that monitors the wavelength of the scanning source. The signals of the reference source and the scanning source can be identified by means of time division multiplexing, wavelength filtering, modulation, or any other suitable technique. Alternatively, the reference source is monitored

by an additional reference device which is representative for the first reference device (for example concerning temperature).

The benefit is improved accuracy if the reference device(s) is (are) more stable than the reference source.

5 This is a condition that is valid for example if (but not only if) the reference device is a highly stable interferometer, while the reference source is a semiconductor laser that dissipates heat and is subject to drift and aging.

Figure 10 shows another improvement for monitoring absolute drift. As compared to Figure 9, we now have two reference sources:

10 • Reference source B is the one as discussed previously. A fraction of its output is incident on the detector on which also a fraction of the scanning source is incident. The wavelength of reference source B is in the scan interval $[\lambda_1 \dots \lambda_2]$, so that the event that this reference wavelength equals the scanning source wavelength occurs at a time t_{ref} within $[t_1 \dots t_2]$ (see Figure
15 5).

• The additional reference source A has a better stability and absolute accuracy than reference source B. Reference source A is for example (but not limited to) a gas laser or Hg lamp, the wavelength of which is dominated by the physical properties of the source, rather than by its design parameters.

20 This highly stable reference source A allows accurate monitoring of the drift of the reference device(s). Knowing the drift of the reference device(s), as well as the drift of reference source B with respect to the reference device(s), we obtain the actual drift of reference source B. We can use knowledge of this drift to correct the wavelength scan for the drift of reference source B, to
25 improve the accuracy of the system. Note that the wavelength of reference source A is not necessarily inside the scan interval $[\lambda_1 \dots \lambda_2]$. If no highly stable source is available in the wavelength range of interest, we can apply the implementation according to Figure 10 to transfer the high accuracy of reference source A to the wavelength range of interest. As previously
30 mentioned, reference source A may monitor the same reference device(s) that

monitor(s) the reference source B and the scanning source, or it may monitor an additional representative reference device. Again time division multiplexing, wavelength filtering, modulation, or any other suitable technique is applied to distinguish between the sources in case these share
5 reference devices.

Two general remarks that are relevant for the development: It should be mentioned that monitoring the reference device(s) and absolute references may be done during each wavelength scan. Effectively, this means operation is as a real-time calibration unit. Alternatively, this monitoring can
10 be done only once, or at regular time intervals. This can be advantageous for example if the amount of optical power is limited, since the calibration will consume a fraction of the available optical power.

Finally, it should be mentioned that the above is written in terms of wavelength scanning of optical sources. However, the concept works also for
15 frequency-scanning of electrical signals. The shared detector is then any suitable component or circuit in which the difference frequency is generated. All other concepts mentioned above are applicable. The reference source is then for example a local oscillator.

Claims

1. A method of characterizing or calibrating a scanning wavelength system, comprising
 - scanning a wavelength of an optical probe signal from a scanning source;
 - supplying a first fraction of the optical probe signal to a device under test;
 - 5 - supplying a second fraction of the optical probe signal to a reference device;
 - supplying a third fraction of the optical probe signal to detector;
 - supplying light at a reference wavelength from a reference source to the detector together with the third fraction;
 - processing a detector signal by electronics and/or software to identify an
 - 10 event that a wavelength of the scanning source substantially equals the reference wavelength.
2. A method according to claim 1, comprising supplying a fraction of light from the reference source to a reference element which is said reference device or a further reference device.
- 15 3. A method according to claim 2, wherein said reference element is said reference device, the method comprising identifying signals due to the scanning source and the reference source by means of time division multiplexing, wavelength filtering, or modulation.
4. A method according to claim 1 or 2, comprising
 - 20 - supplying light from a further reference source to the said reference element together with said fraction of light from the reference source and, if the fraction of light is supplied from the reference source to a reference element which is said reference device or a further reference device, a reference fraction of the optical probe signal, which is the second fraction or a further fraction;
 - 25 - monitoring a drift of the reference element with the light from the further reference source;

- determining a relative drift of the reference source with respect to the reference element;
- determining drift of the reference source based on the drift of the reference element and the relative drift of the reference source with respect to the reference element;
- correcting the wavelength scan using the drift of the reference source.

- 5 5. A method according to claim 4, wherein a wavelength of the further reference source is outside a scan range of the scanning source.
6. A method according to claim 4, wherein the wavelength is scanned repeatedly and the monitoring of the reference element and absolute references during one of the scans is used for calibration of a plurality of scans.
- 10 7. A method according to claim 4, wherein the wavelength is scanned repeatedly and the monitoring of the reference devices and absolute references is done during each wavelength scan.
- 15 8. A method according to claim any one of the preceding claims, wherein the reference source is a reference laser.
9. A method according to any one of the preceding claims, wherein the reference device is a wavelength filter, an interferometer preferably having a periodic wavelength response.
- 20 10. A method according to any one of the preceding claims, wherein the scanning source is a tunable laser or a broadband source combined with a tunable filter.
11. A method according to claim 10, wherein the broadband source is an LED or an ASE source, and/or wherein the tunable filter is a Fabry Perot filter, comprising a piezo-electric device configured to control a cavity length of the Fabry Perot filter.
- 25 12. A computer program product comprising software for programmable computer that, when executed by the computer causes the computer to execute the method of any of the preceding claims.
- 30 13. A scanning wavelength system, comprising

- a scanning source configured to scan a wavelength of an optical probe signal from the scanning source
 - a reference source;
 - a reference device configured to receive a fraction of the optical probe signal;
 - 5 - a detector configured to receive a further fraction of the optical probe signal, and further light from the reference source;
 - electronics and/or software configured to process a detector signal from said detector to identify an event that a wavelength of the scanning source substantially equals the reference wavelength.
- 10 14. A scanning wavelength system according to claim 12, comprising a device under test, configured to receive a yet further fraction of the optical probe signal.
15. A scanning wavelength system according to claim 13 or 14, comprising
- 15 - a further reference source configured to supply light to a reference element that is the reference device or a further reference device, together with said light from the reference source and a reference fraction of the optical probe signal, which is the second fraction or a further fraction; wherein the electronics and/or software are configured to
- 20 - monitor a drift of the reference element with the light from the further reference source;
- determine a relative drift of the reference source with respect to the reference element;
 - determine drift of the reference source based on the drift of the reference
- 25 element and the relative drift of the reference source with respect to the reference element;
- correct the wavelength scan using the drift of the reference source.

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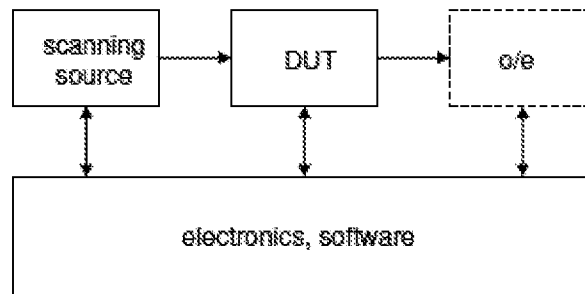


Figure 1

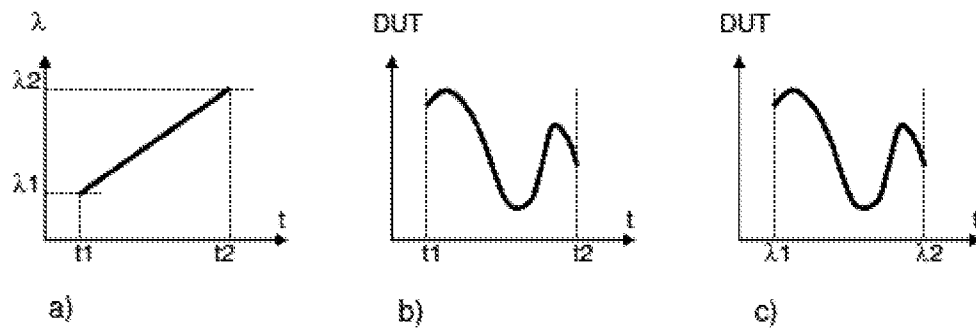


Figure 2

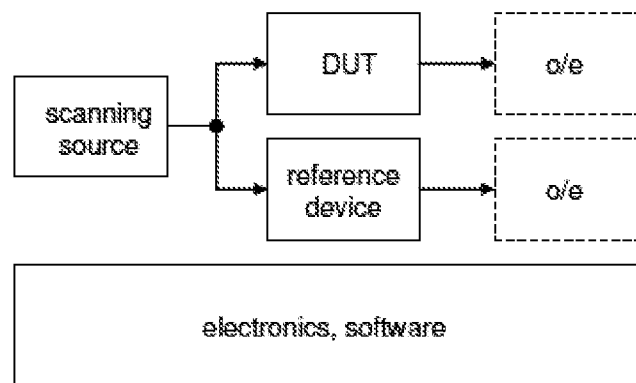


Figure 3

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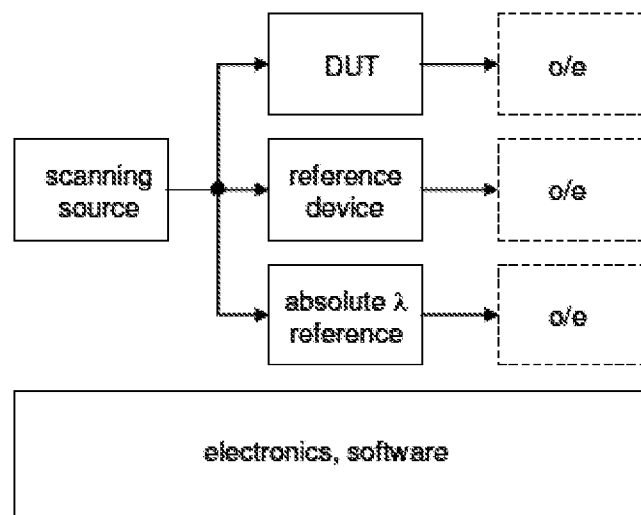


Figure 4

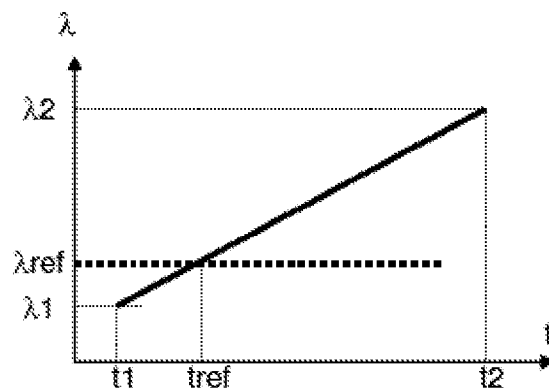


Figure 5

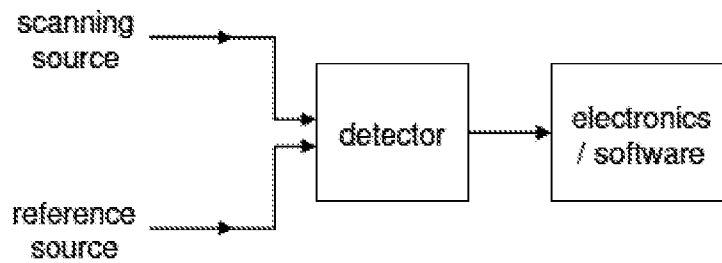


Figure 6

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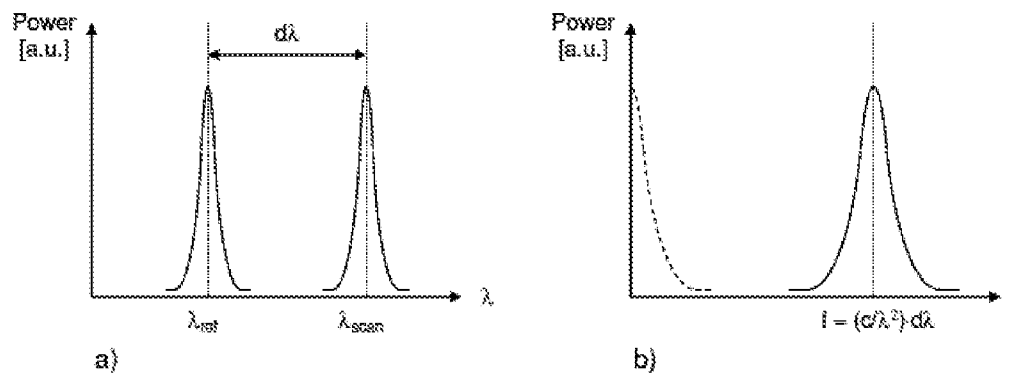


Figure 7

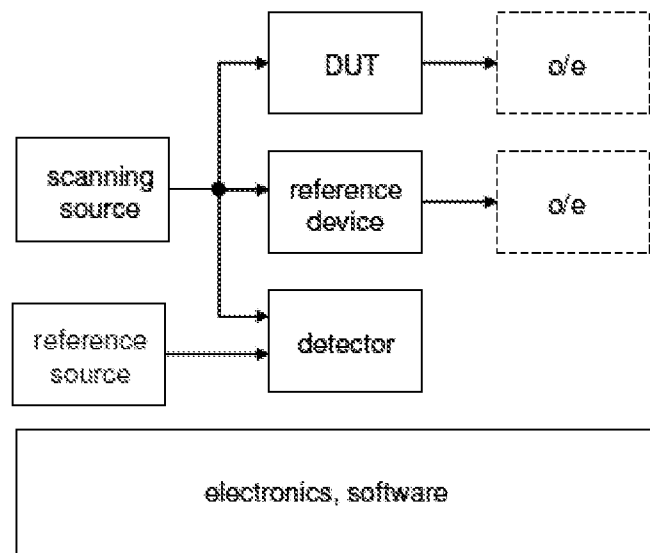


Figure 8

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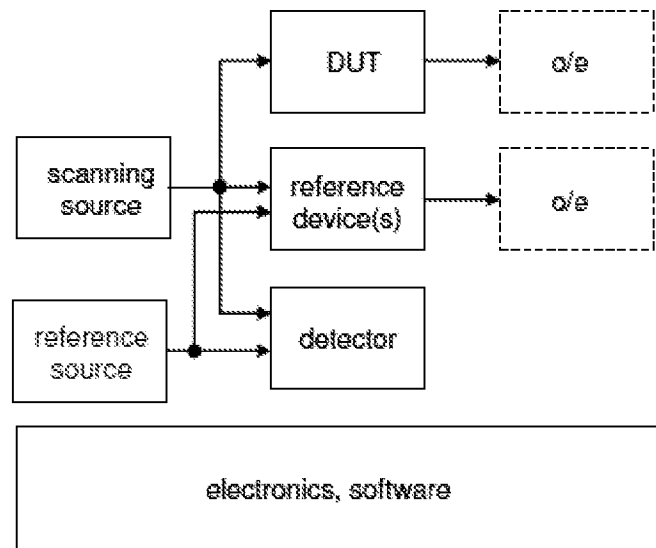


Figure 9

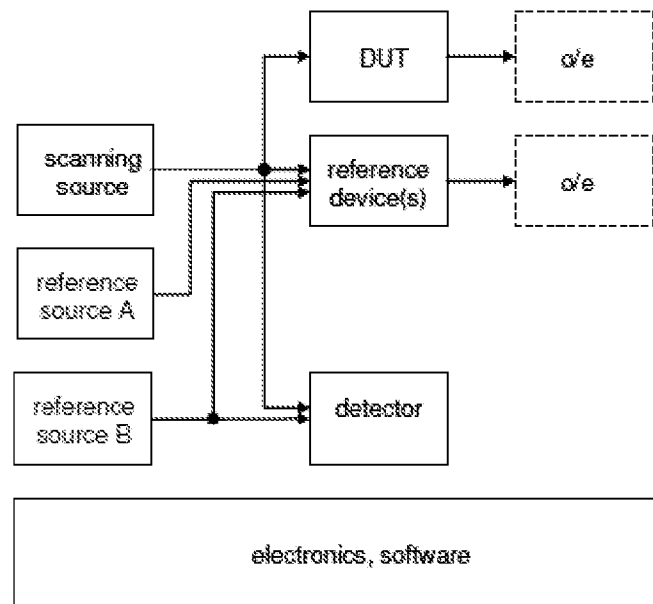


Figure 10

INTERNATIONAL SEARCH REPORT

International application No

PCT/NL2011/050238

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01M11/00 G01D5/353 G01J9/02
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)

G01M G01D G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EP0-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 98/36252 A1 (OPTOPLAN AS [NO]; KRINGLEBOTN JON THOMAS [NO]; THINGBOE DAG [NO]; NAKS) 20 August 1998 (1998-08-20)	1-3,8-14
Y	page 6, line 17 - page 13, line 15; figures 1-10	4-7,15

X	EP 1 207 377 A2 (AGILENT TECHNOLOGIES INC [US]) 22 May 2002 (2002-05-22)	1-3,8-14
Y	paragraph [0065] - paragraph [0081]; figures 9,10	4-7,15

X	WO 2005/024349 A1 (DONAM SYSTEMS INC [KR]; YONG JAE CHUL [KR]; KIM JAE YOUNG [KR]) 17 March 2005 (2005-03-17)	1-3,8-14
Y	page 8, line 1 - page 14, line 19; figures 5-10	4-7,15

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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

5 July 2011

Date of mailing of the international search report

14/07/2011

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Authorized officer

Gruss, Christian

INTERNATIONAL SEARCH REPORT

International application No

PCT/NL2011/050238

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 98/17969 A1 (MICRON OPTICS INC [US]) 30 April 1998 (1998-04-30) cited in the application	1-3,8-14
Y	page 15, line 9 - page 18, line 30; figures 3,7,10-18	4-7,15
Y	----- US 6 870 629 B1 (VOGEL KURT R [US] ET AL) 22 March 2005 (2005-03-22) column 12, line 56 - column 18, line 28; figures 10-17	4-7,15
A	----- US 2006/221344 A1 (MASUDA SHIN [JP] ET AL) 5 October 2006 (2006-10-05) paragraph [0033] - paragraph [0144]; figures 1-8	1-15
A	----- WO 2007/082055 A2 (SUNRISE TELECOM INC [US]; ZENG KE-CAI [US]) 19 July 2007 (2007-07-19) page 7, line 16 - page 17, line 5; figure 2	1-15
A	----- US 6 115 122 A (BAO YUFEI [US] ET AL) 5 September 2000 (2000-09-05) cited in the application column 11, line 1 - column 14, line 48; figures 15-17	1-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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