(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
14 August 2008 (14.08.2008)

PCT

(10) International Publication Number
WO 2008/095923 A1

(51) International Patent Classification:
G02B 27/00 (2006.01) *G02B 26/06* (2006.01)
G02B 26/02 (2006.01)

(21) International Application Number: PCT/EP2008/051392

(22) International Filing Date: 5 February 2008 (05.02.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
07300776.7 6 February 2007 (06.02.2007) EP

(71) Applicant *(for all designated States except US)*: **VARIOPTIC** [FR/FR]; 24A / 24B Rue Jean Baldassini, F-69007 Lyon (FR).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **BERGE, Bruno** [FR/FR]; 3, Place des Célestins, F-69002 Lyon (FR).

(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, 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, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, 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, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

(54) **Title:** ELECTROWETTING BASED OPTICAL ELEMENT AND OPTICAL IMAGING DEVICE USING SUCH

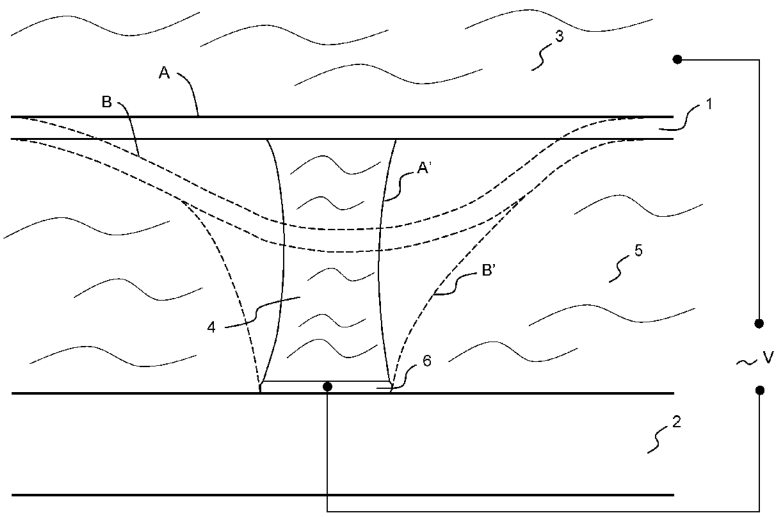

FIG.1

(57) **Abstract:** An electrowetting based optical element comprising: a substrate (2) and a deformable membrane (1) mechanically coupled to said substrate, said substrate and membrane defining a fluid chamber, an insulating liquid (5) and an electrically conductive liquid (4) immiscible with said insulating liquid, one of the liquids filling said fluid chamber andthe other liquid being arranged so as to form one or a plurality of liquid bridges between the substrate and the membrane to ensure said coupling, the shape of the at least one liquid bridge being controlled by electrowetting under the application of at least one voltage, resulting in a local deformation of the membrane.

WO 2008/095923 A1

ELECTROWETTING BASED OPTICAL ELEMENT AND OPTICAL IMAGING DEVICE USING SUCH.

Field of the invention

The present invention relates to an electrowetting based optical element, particularly an optical element for optical phase corrections which is capable of reversibly and precisely modifying the optical path of light rays under the application of a voltage. This element can be applied in a broad range of optical systems or optoelectronic devices, e.g. imaging lenses or zooms to be used for example in digital cameras, camcorders or mobile phone cameras.

Description of the prior art

Adaptive optical actuators for control of the optical path of light rays are already known and usually use deformable mirrors. In addition to being very expensive, the fact that they use reflective surfaces makes them very difficult to integrate in simple imaging systems where the space constraint is strong. Therefore they are mostly used in large telescope systems or in complex optical arrangements for research applications, e.g. in microscopy, or in ophthalmology.

Transmission based optical actuators for optical phase control are also known, the main devices used today being based on liquid crystals matrices. The index of refraction of the liquid crystal matrix is locally changed by control of the orientation of the molecules under the application of an electrical signal, resulting in the control of the phase shift introduced at each pixel of the matrix. One drawback of such liquid crystals devices is that they usually use polarized light, thus absorbing half of the incident light intensity.

US 4,030,813 describes another optical actuator, based on the control of a liquid slab by electro-osmosis. In this publication the authors mention the use of a liquid layer on top of a digitized electrode system. By addressing different voltages to the electrodes, spatially variable phase shifts are obtained. But this arrangement is only suitable for very small systems: for sizes larger than one millimetre, the liquids won't be able to be maintained in place , due to flows induced by gravity or accelerations. Therefore such device is not usable in major optical systems.

Summary of the invention

The present invention concerns an electrowetting based optical element for the spatial control of the optical phase of an optical beam, that can be used in transmission, and is controlled by one or several electric signals.

According to the invention, the optical element comprises a substrate and a deformable membrane mechanically coupled to said substrate, and defining a fluid chamber, an insulating liquid and an electrically conductive liquid immiscible with said insulating liquid, one of the liquids filling said fluid chamber and the other liquid being arranged so as to form one or a plurality of liquid bridges between the substrate and the membrane to ensure said coupling, the shape of the at least one liquid bridge being controlled by electrowetting under the application of at least one voltage, resulting in a local deformation of the membrane.

According to the invention, the liquid bridges will serve as actuators using electrowetting to induce pulling or pushing forces on the membrane.

The shape and number of such actuators is variable, from 1 to 3 for simple systems, up to millions for large digitalized systems.

Advantageously, the deformable membrane and the substrate are transparent and the first and second liquids are transparent as well and have substantially the same indices of refraction, making it possible to have a transmissible optical element for optical phase corrections.

The invention can be advantageously applied to make a variable aspheric correction lens, to be used for example in imaging systems. The shape of the aspheric lens according to the invention is monitored by external electrical signals, making it very attractive for a large number of optical systems, including consumer systems, where aspheric lenses are more and more often integrated. In particular, the variable aspheric lens according to the invention can be used for the correction of optical aberrations in imaging systems, for example imaging systems using zooms, to compensate the optical aberrations when the zoom ratio is varied. It enables to increase the zoom ratio of a system, by allowing to increase the aberration correction. It can also enable to simplify the design of the zoom, by reducing the number of mobile groups in the zoom lens, making the overall size of the system very small.

Brief description of the drawings

The characteristics and advantages of the invention are better explained in the following description, illustrated by the figures that represent:

- Figure 1, a first embodiment of the optical element according to the invention, using three liquids;
- Figure 2, a second embodiment of the optical element according to the invention where only two liquids are used;
- Figure 3, a 2D regular arrangement of a plurality of liquid bridges, thus allowing a digitalized spatial control of the pulling or pushing forces on the membrane;
- Figure 4, an arrangement of ring shaped liquid bridges to make a variable aspheric lens;
- Figure 5, a cross section view of the figure 4;
- Figure 6, a zoom system including an optical element according to the invention.

Description of the invention

Figure 1 shows a first embodiment of an optical control element according to the present invention. A transparent and deformable membrane 1 is stretched above a transparent substrate 2. The gap between the membrane and the substrate forms a fluid chamber filled with an insulating liquid 5 (usually a polar oil). Inside this insulating liquid, one or several liquid bridges are made between said substrate 2 and membrane 1 using another liquid 4, electrically conductive, non miscible with liquid 5 . The liquid bridge 4 is positioned on an electrode 6 arranged on the substrate 2, the surface energy and polarity of the electrode 6 being chosen such that the liquid bridge 4 is spontaneously maintained over the electrode 6. In this embodiment, a third liquid 3, electrically conductive, is arranged over the membrane surface. When a voltage difference is applied between an electrode in contact with the liquid 3 (not shown on figure) and the electrode 6 the contact angle of the liquid 4 on the membrane lower surface will change, based on an electrowetting effect. This change of the contact angle induces a force normally to the surface of the membrane: this force will pull the membrane towards the substrate 2, resulting in a local deformation of the membrane. On the figure, A,A' (respectively B,B') are the positions of the membrane and bridge at 0V (respectively maximum voltage).

Advantageously, the liquids 4 and 5 are chosen to have identical or very similar indices of refraction n_4 and n_5 such that optically the layer made of the substrate, the membrane and the liquids 4 and 5 is seen as an optically homogeneous layer by an incident light beam. As a consequence the liquid bridge constituted by the interface between liquids 4 and 5 does not deviate nor reflects the light rays. Liquid 3 is chosen to have a different index of refraction n_3 so that an incident light beam passing through the element will experience the phase shifts induced by the local displacements of the membrane. The optical axis, not shown on figure 1, is perpendicular to the membrane. Locally the phase shift, in radian, will be given by :

$$\delta\varphi = 2\pi/\lambda \, (n_3-n_4) \, \delta\xi \quad ,$$

Where λ is the wavelength of the incident light beam, $\delta\xi$ is the local deformation of the membrane compared to the non-deformed planar state.

The local deformation $\delta\xi$ is related to the local force applied by the liquid bridge. It can be shown that the force induced by the liquid bridge on the membrane is of the order of:

$$F \sim (\varepsilon\varepsilon_0 \, v_0 \, / \, 4 \, D^2 \, d) \, V^2$$

Where ε is the dielectric constant of the membrane, ε_0 is the vacuum permittivity, v_0 is the volume of the liquid bridge, D is the length of the bridge (D is also the gap thickness, or the distance separating the membrane 1 from the support 2), d is the thickness of membrane 1 and V is the voltage between electrode 6 and liquid 3.

It can be shown that this force, although very weak, is amplified by the presence of the liquid bridge by a factor D/d: if there was no liquid bridge 4, a force would be also acting from the distant interaction of the electrode 6 and the liquid 3 which are both electrical conductors. The applicant has shown that the liquid bridge 4 is acting as a medium transmitting the electrical force through the oil layer of thickness D.

Practically the ratio D/d can be of the order of 5 to 100: a practical application could use a membrane of d=5µm thickness , oil layer thickness D =200µm, thus leading to a 40x amplification factor.

Contrary to the cited prior art US 4,030,813, there is no size limitation to the optical element: due to the membrane tension, even if the three liquids 3,4,5 have different densities (typically ranging from 800 kg/m^3 up to 2000 kg/m^3), the gravity forces will not impact the shape of the membrane. The applicant has shown that the maximum size of such device could be 50mm fully usable pupil diameter in case of a membrane stretched at a lateral tension 100 N/m and 10mm in case of a reduced lateral tension of 1N/m.

The insulating liquids can be obtained by mixing conventional non polar oils like silicon compounds, and the conductive liquids can be made using water soluble molecules or salts like $ZnBr_2$, LiBr, LiCl, or $CaCl_2$. Advantageously, these compounds will be used at relatively high concentration (>40%), in order to fulfil the relation $n_3=n_4$.

On figure 1 the liquid layer 3 is confined by a glass window which is not shown on the figure. Obviously, liquid 3 could be replaced by a transparent electrode deposited on the top surface of the membrane. This transparent electrode would then have to be also deformable, in order to follow the membrane's deformations without degradations.

Figure 2 shows an other example of an optical element according to the invention. A membrane 1 is stretched over a substrate 2 covered with the electrode 6. The electrode 6 is covered with an insulating/hydrophobic layer 7 for electrowetting. The gap between the membrane and the substrate is filled with a conducting liquid 15. In this example, the insulating liquid 14 forms a liquid bridge between the membrane and the support. Under the application of a voltage V between the conducting liquid 15 and the electrode 6, the liquid bridge 14 contracts, inducing a normal force to the surface of the membrane that pushes the membrane 1 away from the substrate 2. A,A' (respectively B,B') are the positions of the membrane and bridge at 0V (respectively maximum voltage).

Figures 3 and 4 show two different arrangements of the liquid bridges within the fluid chamber of the optical control element, to control the deformation of the membrane.

Figure 3 shows an arrangement with a bi dimensional matrix of liquid bridges, whose shapes are electrically controlled to produce a 2D pattern of controlled phase shifts . This arrangement can be used for example for a bi dimensional correction phase element in an adaptive optical system.

Figures 4 and 5 show another arrangement with concentric liquid bridges, each liquid bridge having a ring shape and being arranged between the substrate 2 and the membrane. This arrangement enables to produce a phase shift pattern with a rotational symmetry to make for example a variable aspheric lens. For example, the central liquid bridge 21 has a disk shape, the other liquid bridges 22,23 etc.. have a toric shape with increasing radii. Figure 5 is a cross section of the Figure 4 along the axis AA.

In the example of figure 4 and 5, it is possible to arrange holes in the membrane, or channels in the base plate 2 in order to make the different inter-bridges compartments communicate, and allow a full amplitude of the deformation.

Figure 6 shows an example of an application of the present invention in a zoom lens arrangement. A set of lenses (67, 68, 69) are used as an optical module, for instance as a zoom lens. In such a zoom lens, the lenses 67, 68, 69 can be optical groups made of several elementary lenses. Each group can be moveable or fixed. Usually, zoom lenses contain 2 or more movable groups, and one difficulty is to keep all optical aberrations as small as possible, whatever the position of the movable groups. It is a great difficulty for the optical designer to make a lens arrangement in which the spherical aberration is corrected in the wide angle mode, as well as in the telephoto mode. This difficulty often results in a limitation in the performances of the zoom lens. According to the zoom lens of figure 6, an optical element (70) according to the invention is arranged inside the zoom lens in order to compensate for example for at least some of the spherical aberrations. The voltages sent to the different liquid bridges (actuators) are chosen according to the zoom ratio, in order to best compensate the spherical aberration for all zoom ratios.

It will be obvious for the man skilled in the art that not only the spherical aberration can be compensated by the electrowetting based optical control element. All other aberrations which require phase shifts ξ(r) fitted by higher order polynomials can be corrected. The only requirement will be that the resolution of the actuators, given by their lateral pitch, is sufficient to produce high order polynomials phase shifts.

The electrowetting based control optical element according to the invention can also be used in all optical systems where adaptive optics is necessary, e.g. imaging systems in astronomy including corrections of disturbances coming from the atmospheric turbulences, free-air telecommunication systems, military applications. It can also be applied for the correction of phase shifts induced by inhomogeneities of a medium situated between an object and the sensor looking at the object, for instance: microscopic observations through a turbid medium (cytoplasm, biological tissues etc…), ophthalmologic observation of the retina through degraded crystalline lens, etc.

Although a transmissible optical element has been described in the above examples, it is possible to make the membrane metallic and the optical element reflexive for specific applications.

CLAIMS

1. An electrowetting based optical element comprising:
   - a substrate (2) and a deformable membrane (1) mechanically coupled to said substrate, said substrate and membrane defining a fluid chamber,
   - an insulating liquid (5) and an electrically conductive liquid (4) immiscible with said insulating liquid, one of the liquids filling said fluid chamber and the other liquid being arranged so as to form one or a plurality of liquid bridges between the substrate and the membrane to ensure said coupling, the shape of the at least one liquid bridge being controlled by electrowetting under the application of at least one voltage, resulting in a local deformation of the membrane.

2. The optical element of claim 1, wherein the fluid chamber is filled with the insulating liquid and the at least one liquid bridge is made with the conductive liquid.

3. The optical element of claim 2, wherein said conductive liquid is in contact with one or a plurality of electrodes (6) arranged on the internal surface of the substrate.

4. The optical element of claims 2 or 3, comprising a third liquid, electrically conductive, arranged above the top surface of the membrane, and acting as an electrode.

5. The optical element of claims 2 or 3, comprising an electrically conducting coating disposed on one of the surfaces of the membrane and acting as an electrode.

6. The optical element of claim 1, wherein the fluid chamber is filled with the conductive liquid and the at least one liquid bridge is made with the insulating liquid.

7. The optical element of claim 6, further comprising one or a plurality of electrodes (6) arranged on the internal surface of the substrate and an insulating layer (7) disposed on the surface of said at least one electrode.

8. The optical element of any of the previous claims, wherein the indices of refraction of said insulating and conductive liquids within the fluid chamber are substantially identical, and all constitutive parts of the optical element are transparent.

9. The optical element of claim 8, which is a transmissible optical phase corrector.

10. The optical element of claim 9, which is a variable aspheric lens, with a plurality of ring shaped liquid bridges arranged according to a rotational symmetry.

11. An imaging system including an optical element of any of claim 9 or 10.

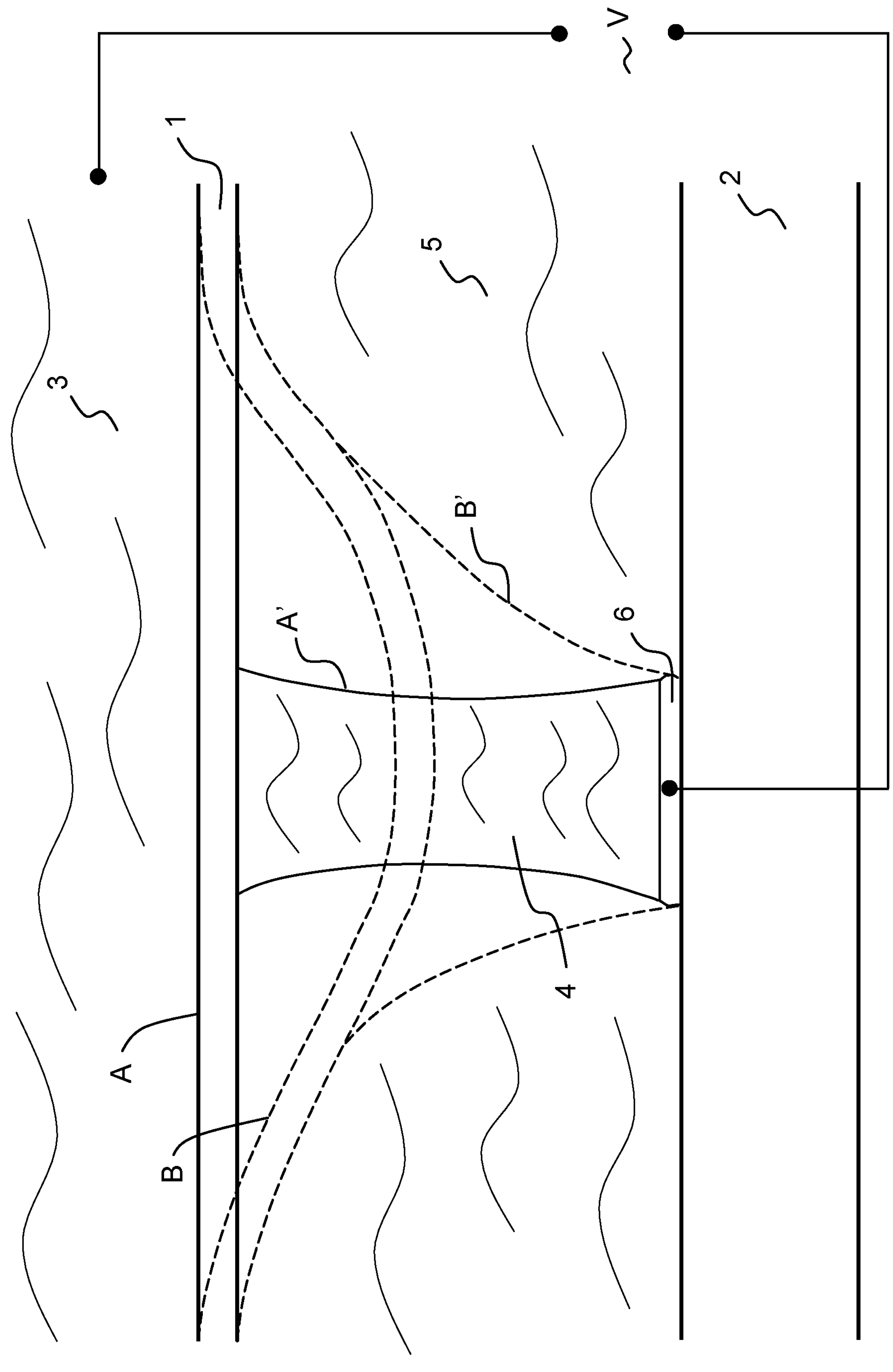

FIG.1

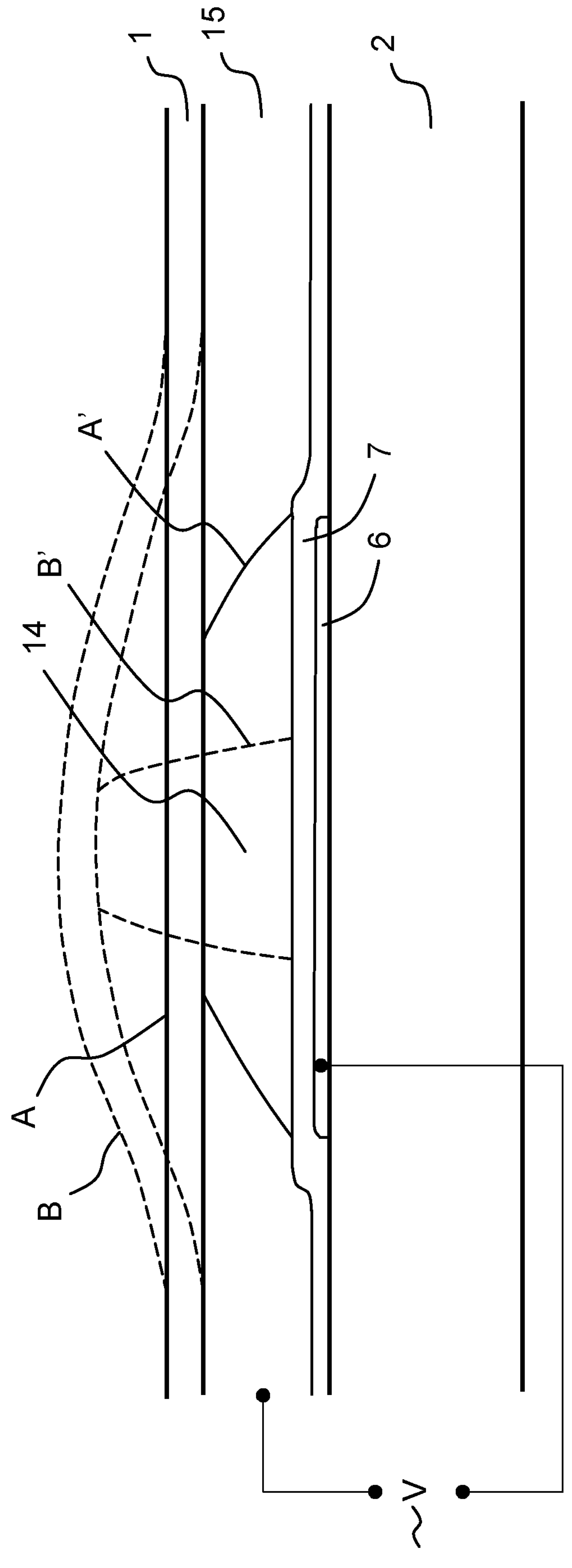

FIG.2

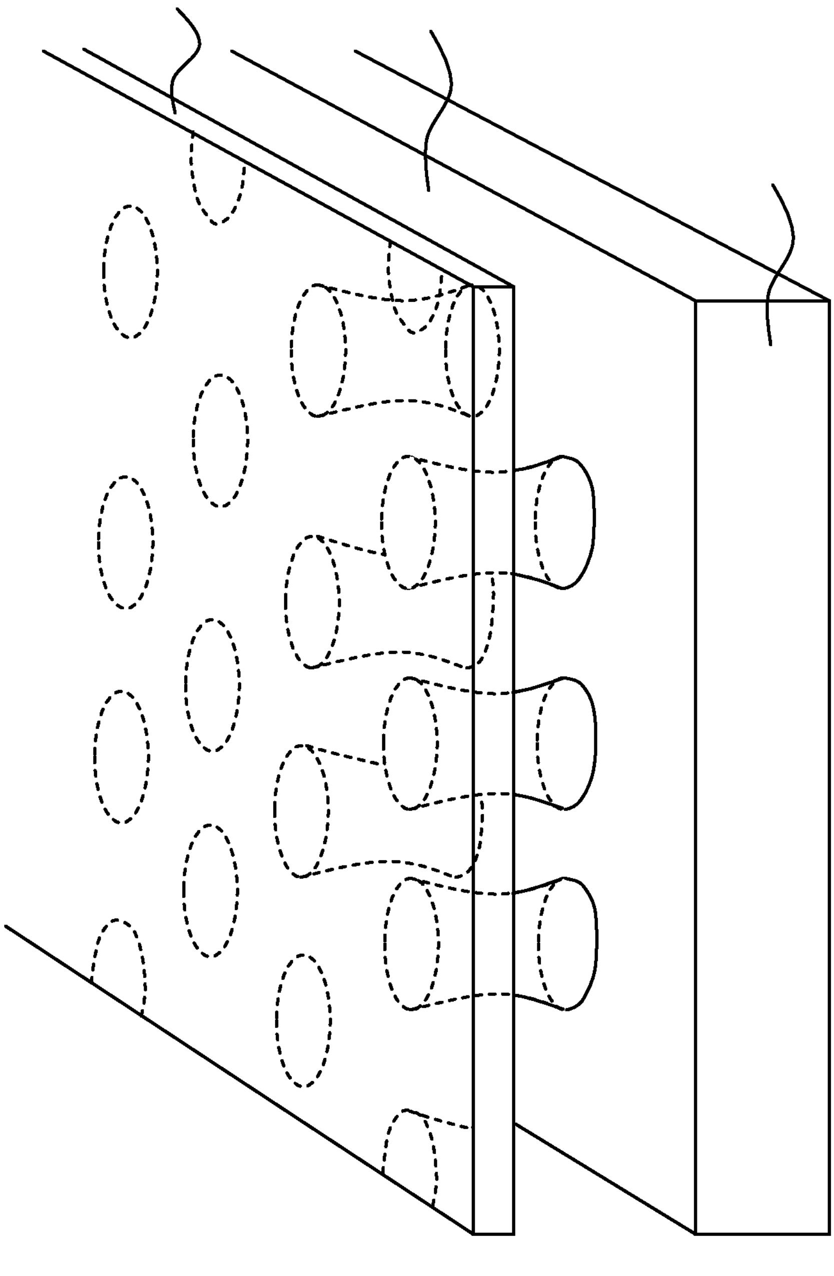

FIG.3

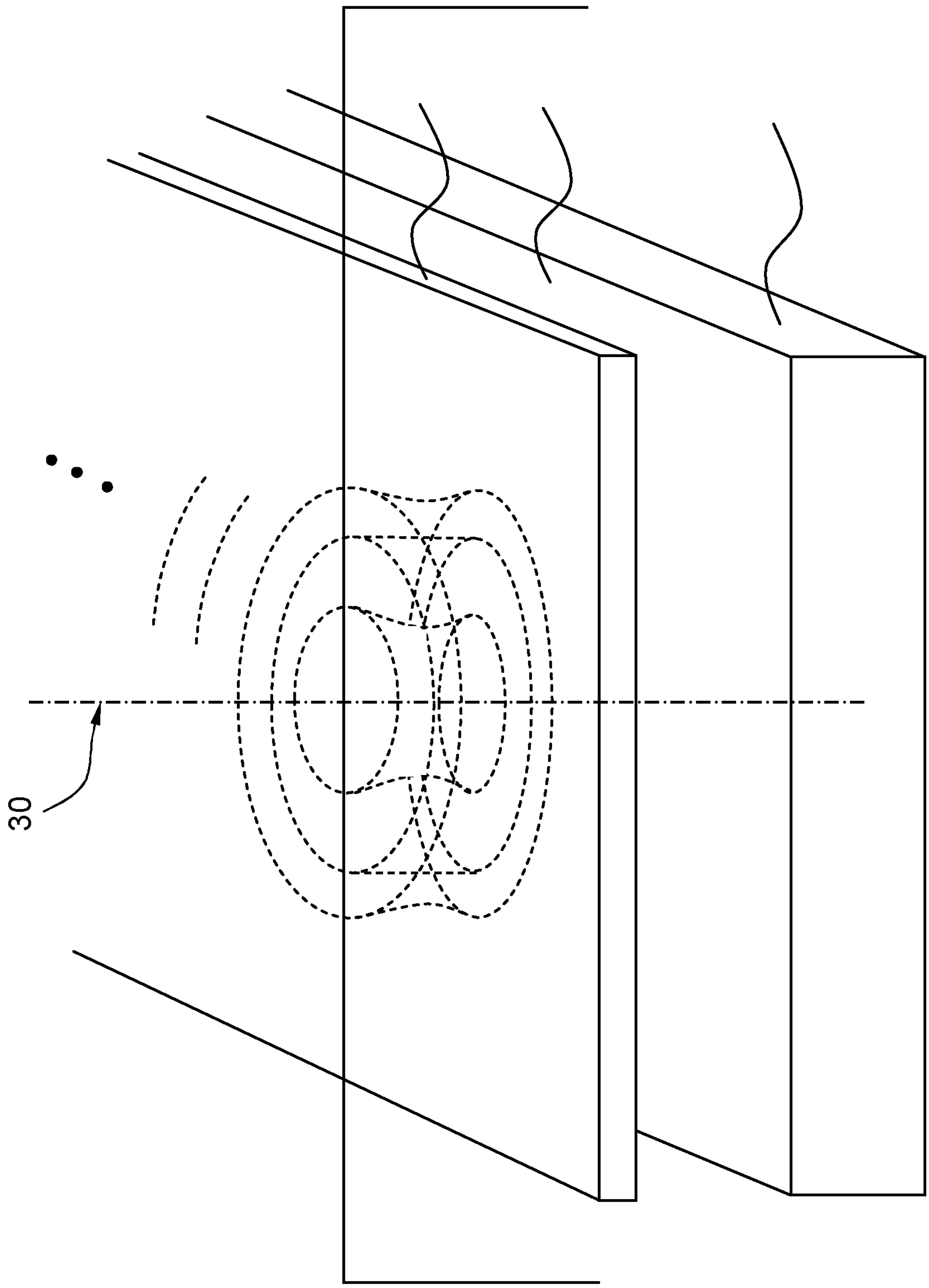

FIG. 4

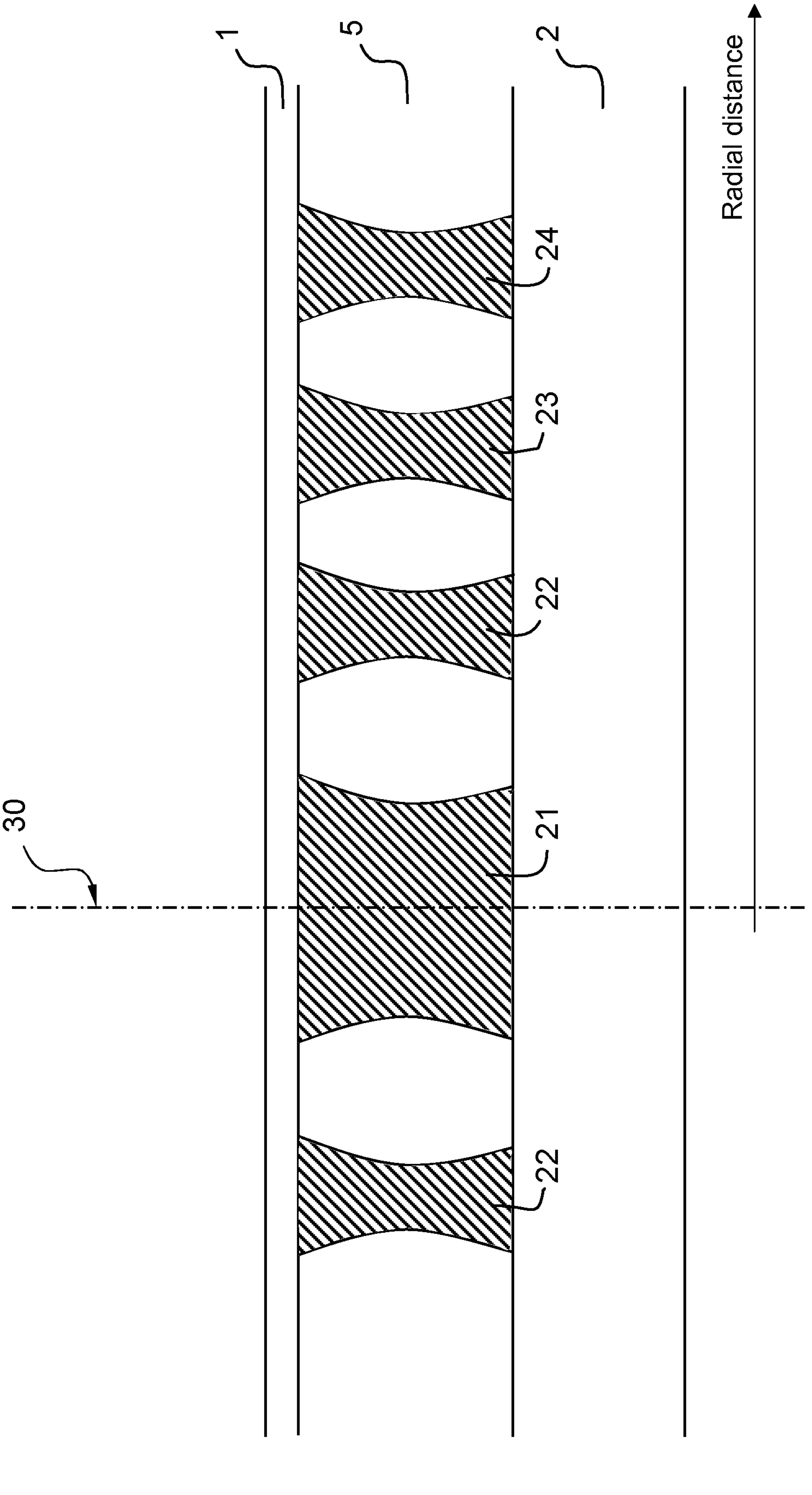

FIG.5

CUT AA

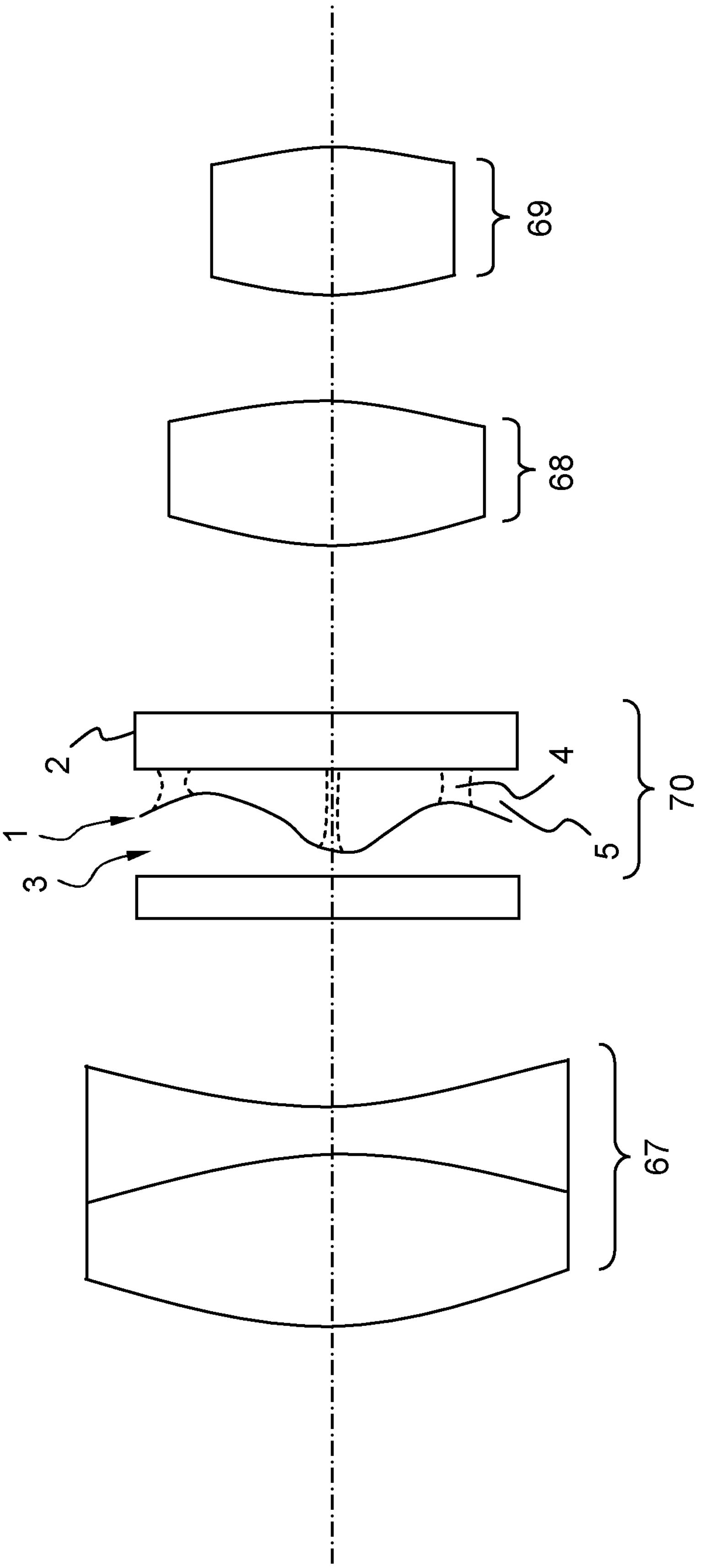

FIG.6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2008/051392

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B27/00 G02B26/02 G02B26/06

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)
G02B

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	FR 2 889 633 A (COMMISSARIAT ENERGIE ATOMIQUE [FR]) 9 February 2007 (2007-02-09) abstract figures 1,4-10 page 14, line 13 - page 17, line 9 page 22, line 16 - page 23, line 2 page 24, line 19 - page 34, line 26	1-3,5, 8-11
A	US 4 030 813 A (KOHASHI TADAO ET AL) 21 June 1977 (1977-06-21) cited in the application abstract column 3, line 54 - column 6, line 26 figures 1-3	1-11

-/--

[X] Further documents are listed in the continuation of Box C.

[X] 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 document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 May 2008	09/06/2008

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Schenke, Cordt

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2006/084653 A (ZEISS CARL MEDITEC AG [DE]; MOHR THOMAS [DE]; DICK MANFRED [DE]; KUEHN) 17 August 2006 (2006-08-17) abstract page 7, line 31 - page 11, line 16 figures 1-11	1-11

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2008/051392

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
FR 2889633	A	09-02-2007	EP	1913433 A2	23-04-2008
			WO	2007017495 A2	15-02-2007
US 4030813	A	21-06-1977	CA	1044816 A1	19-12-1978
WO 2006084653	A	17-08-2006	DE	102005005933 A1	17-08-2006
			EP	1846782 A1	24-10-2007