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(2013.01); **G06F 2203/04109** (2013.01)(72) Inventor: **Ola Wassvik**, Rossby (SE)(21) Appl. No.: **15/112,135**(22) PCT Filed: **Jan. 16, 2015**(86) PCT No.: **PCT/SE2015/050044**

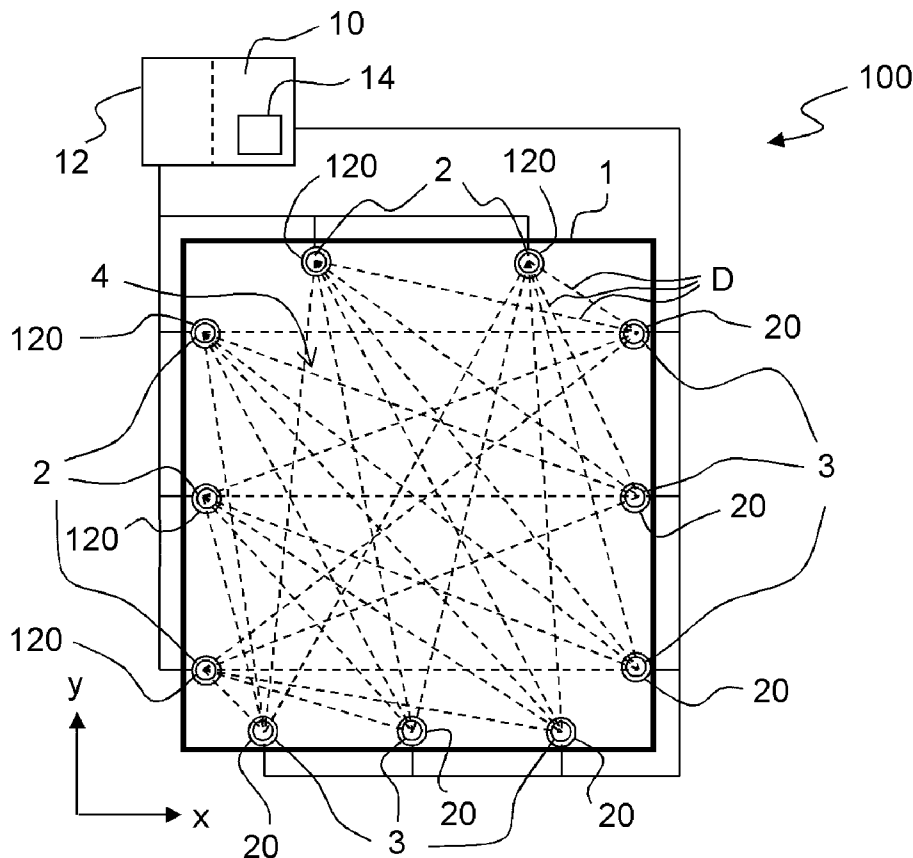
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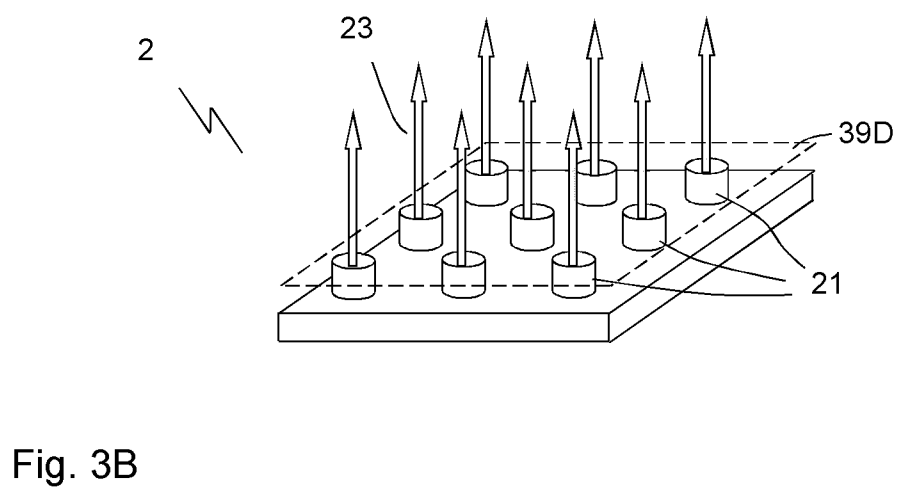
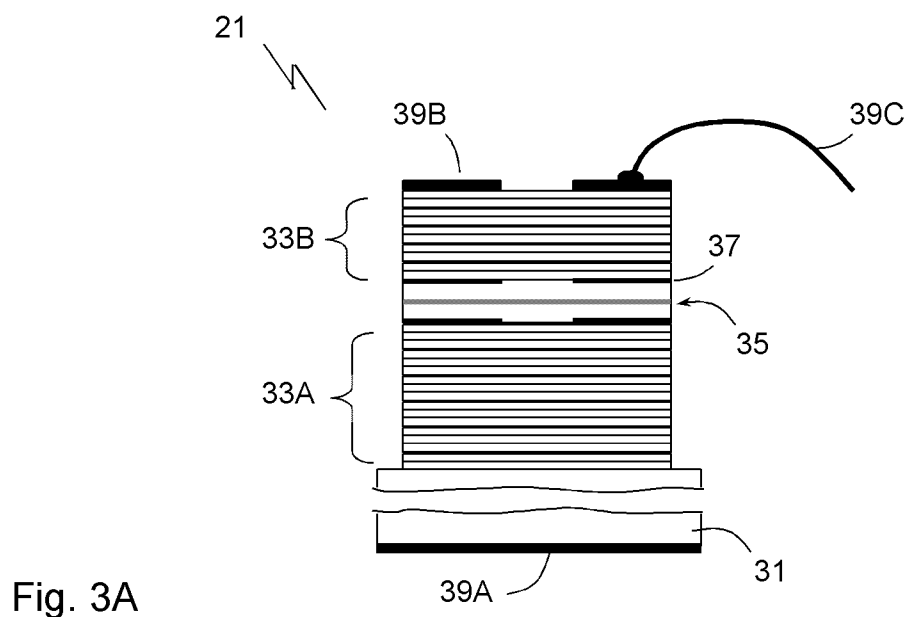
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Jan. 16, 2014 (SE) 1450039-1

(57) **ABSTRACT**

A touch-sensitive apparatus operates by light frustration (FTIR) and comprises a light transmissive panel that defines a front surface and a rear surface, light emitters optically connected to the panel so as to generate light that propagates by total internal reflection inside the panel, and light detectors optically connected to the panel so as to define a grid of propagation paths inside the panel between pairs of light emitters and light detectors. Each of said light emitters is a VCSEL array, each said VCSEL array including a plurality of VCSELs driven in parallel to collectively form one light emitter. Preferably, each light detector is optically connected to the panel via an angular filter, tailored to pass light to the detector in an angular range in which the emitters operate.





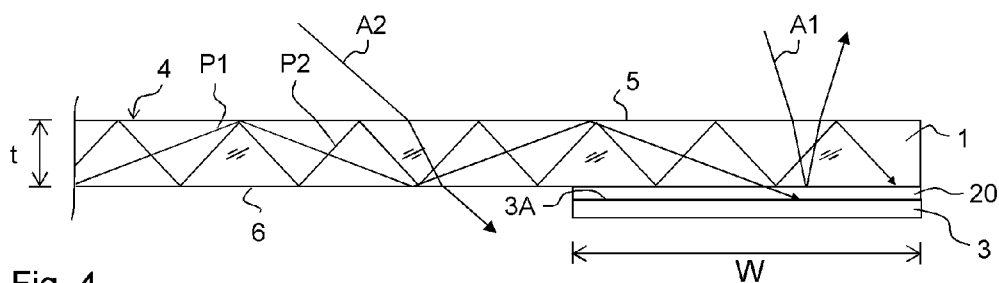


Fig. 4

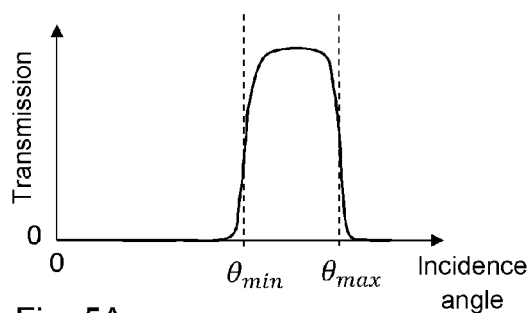


Fig. 5A

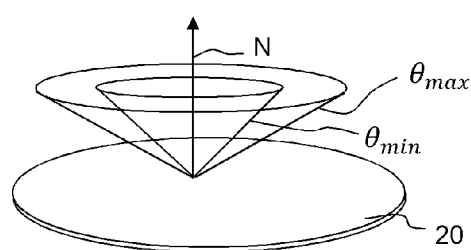


Fig. 5B

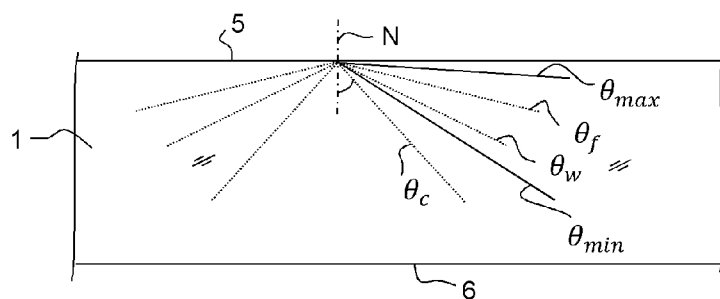


Fig. 6

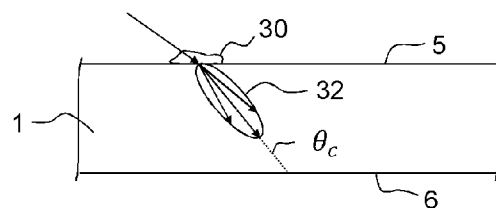


Fig. 7

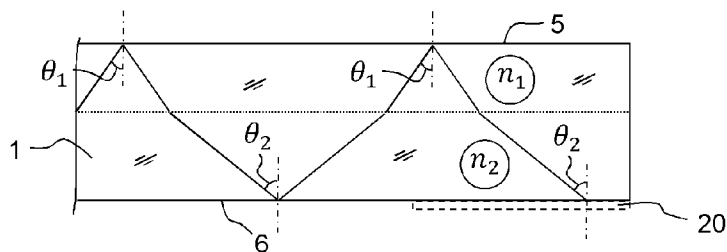


Fig. 8

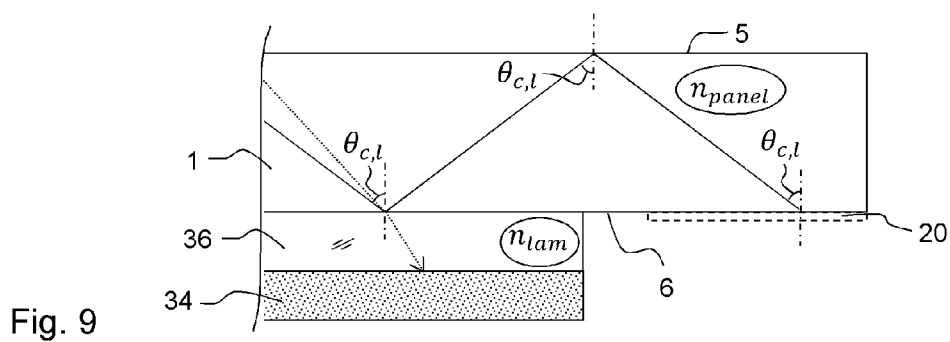


Fig. 9

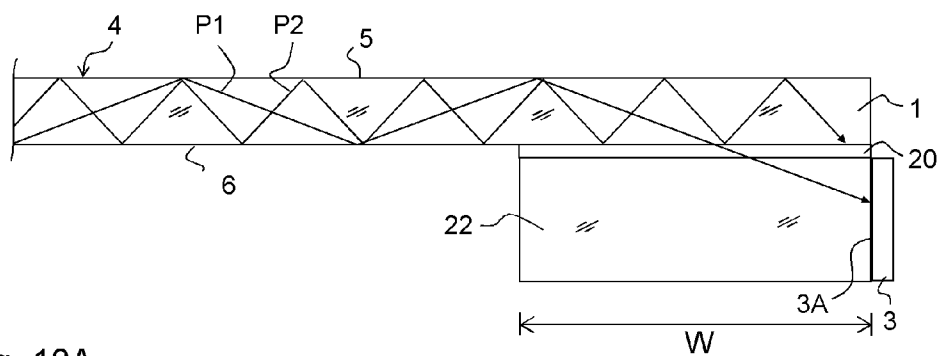


Fig. 10A

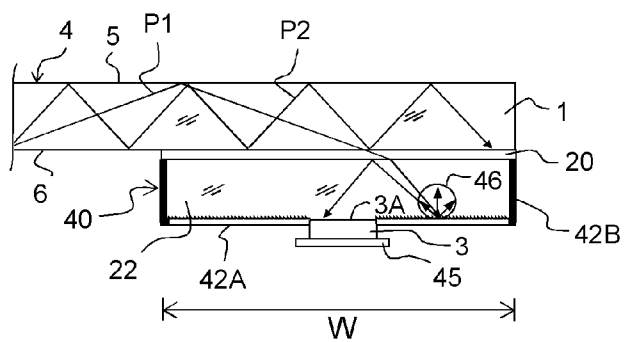


Fig. 10B

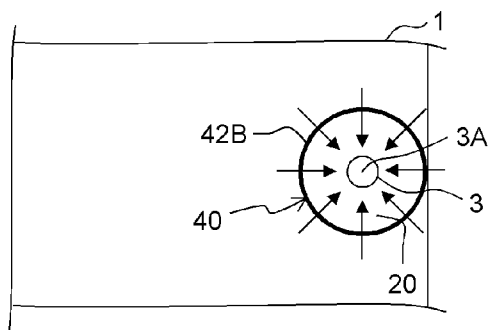


Fig. 10C

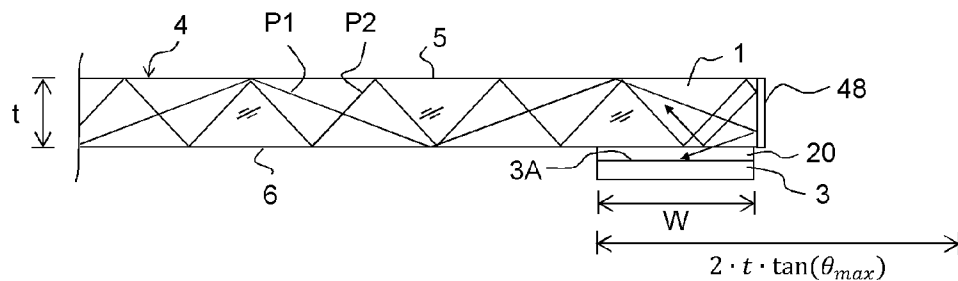


FIG. 10D

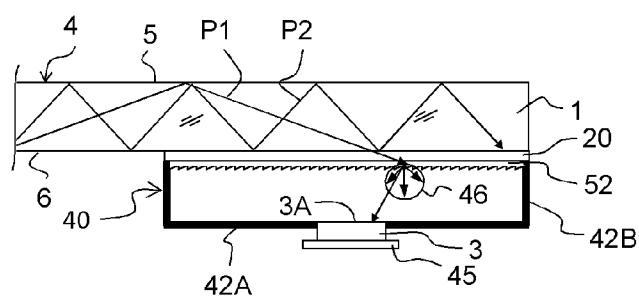


Fig. 10E

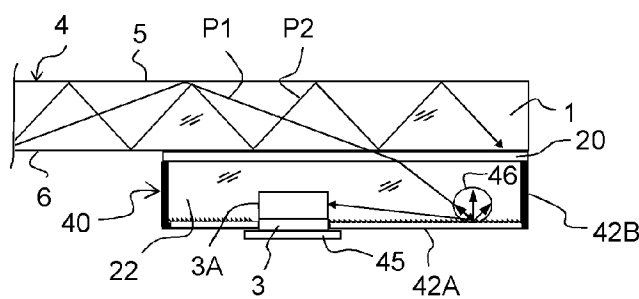


Fig. 10F

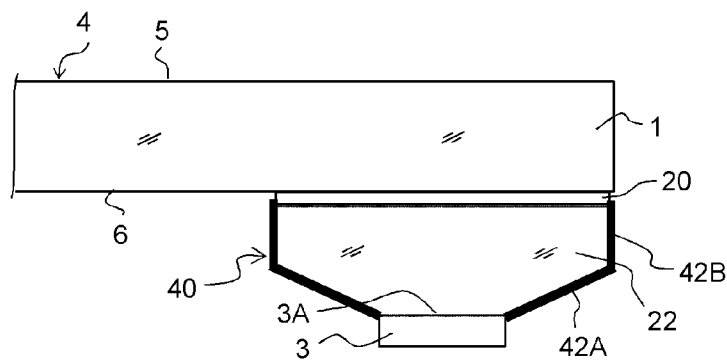


Fig. 10G

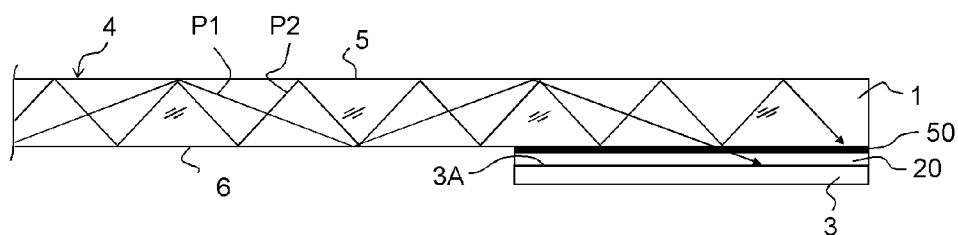


Fig. 10H

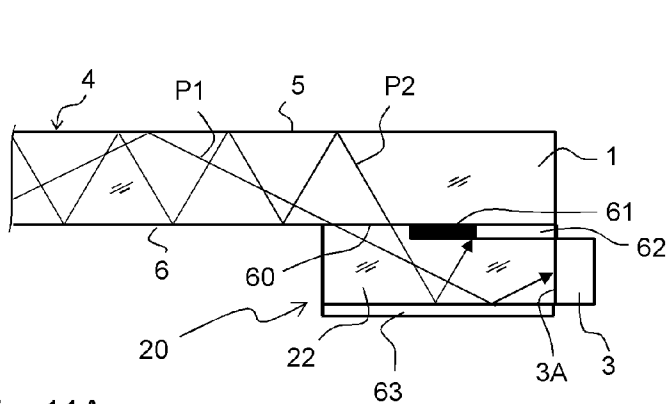


Fig. 11A

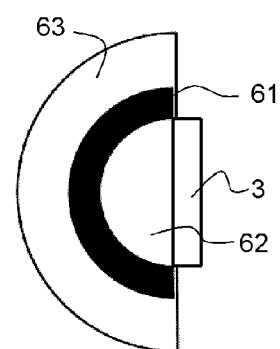


Fig. 11B

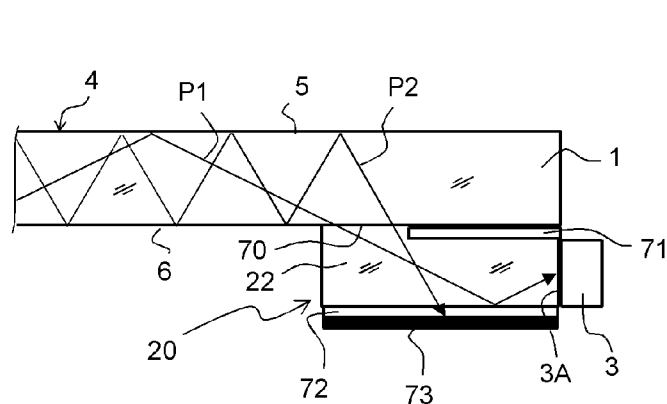


Fig. 12A

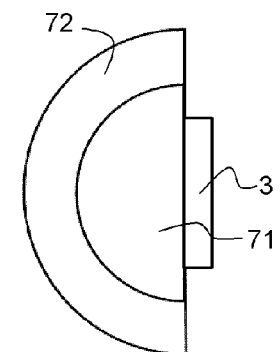


Fig. 12B

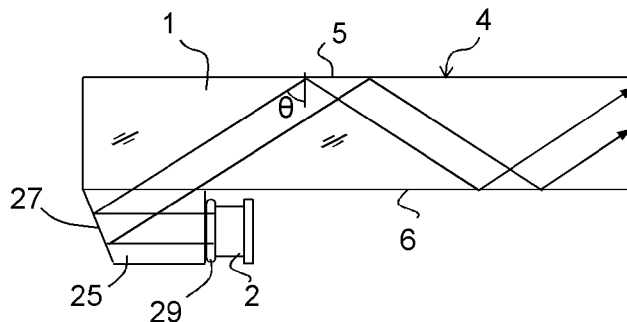


Fig. 13A

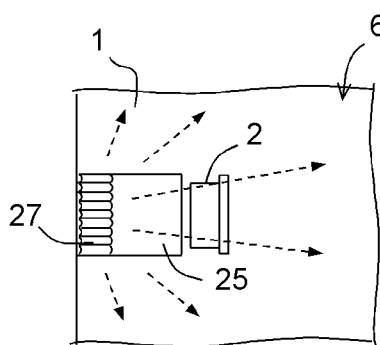


Fig. 13B

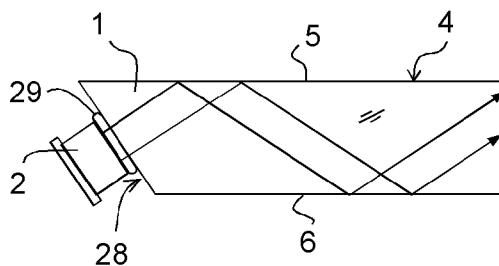


Fig. 13C

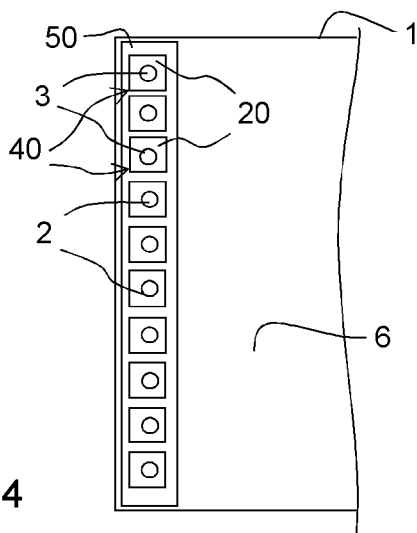


Fig. 14

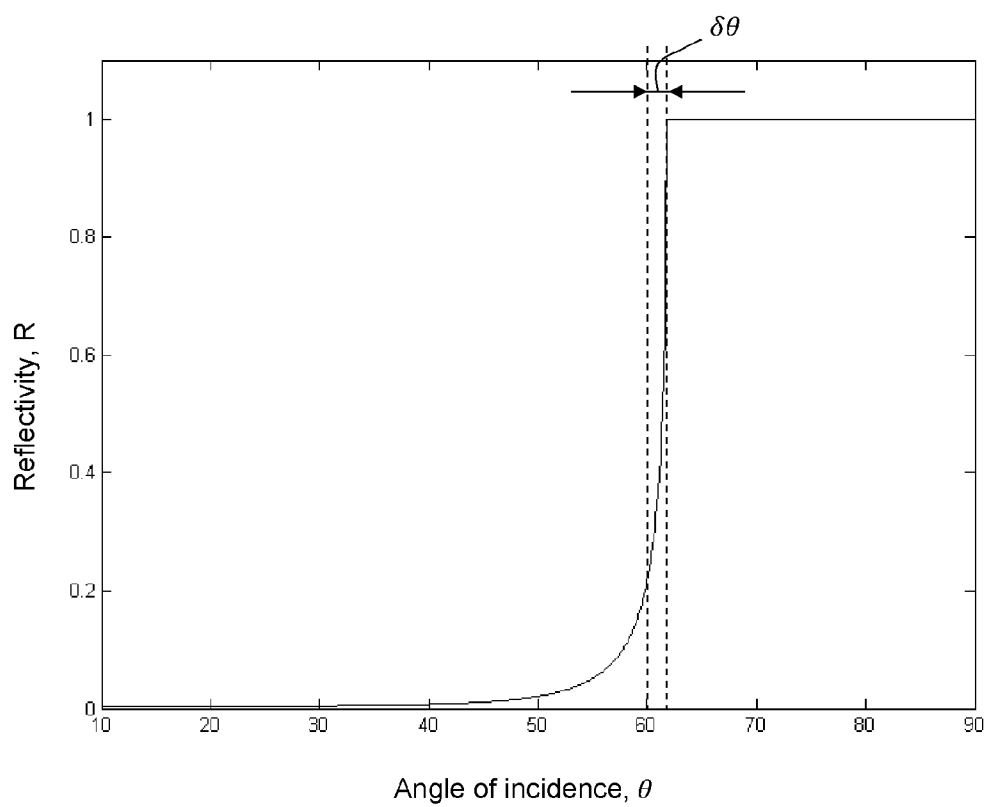


Fig. 15

IMPROVEMENTS IN TIR-BASED OPTICAL TOUCH SYSTEMS OF PROJECTION-TYPE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of Swedish patent application No. 1450039-1, filed 16 Jan. 2014.

TECHNICAL FIELD

[0002] The present invention generally relates to optical touch-sensing systems, and in particular to such systems that operate by projection measurements of light that propagates by total internal reflection (TIR) inside a light transmissive panel.

BACKGROUND ART

[0003] Touch-sensing systems (“touch systems”) are in widespread use in a variety of applications. Typically, the touch systems are actuated by a touching object such as a finger or stylus, either in direct contact, or through proximity (i.e. without contact), with a touch surface. Touch systems are for example used as touch pads of laptop computers, in control panels, and as overlays to displays on e.g. hand held devices, such as mobile telephones. A touch panel that is overlaid on or integrated in a display is also denoted a “touch screen”. Many other applications are known in the art.

[0004] There are numerous known techniques for providing touch sensitivity, e.g. by incorporating resistive wire grids, capacitive sensors, strain gauges, etc into a touch panel. There are also various types of optical touch systems, which e.g. detect shadows cast by touching objects onto a touch surface, or detect light scattered off the point(s) of touching objects on a touch panel.

[0005] One specific type of optical touch system uses projection measurements of light that propagates on a plurality of propagation paths inside a light transmissive panel that defines a touch surface. The projection measurements thus quantify a property, e.g. power, of the light on the individual propagation paths, when the light has passed the panel. The light propagates inside the panel by total internal reflection (TIR) against the touch surface, such that objects on the touch surface causes the propagating light on one or more propagation paths to be attenuated, commonly denoted FTIR (Frustrated Total Internal Reflection). For touch determination, the projection measurements may be processed by simple triangulation, or by more advanced image reconstruction techniques that generate a two-dimensional distribution of disturbances on the touch surface, i.e. an “image” of everything on the touch surface that affects the measured property. Examples of such touch systems are found in U.S. Pat. No. 3,673,327, U.S. Pat. No. 4,254,333, U.S. Pat. No. 6,972,753, U.S. Pat. No. 7,432,893, US2006/0114237, US2007/0075648, WO2009/048365, US2009/0153519, WO2010/006882, WO2010/064983, WO2010/134865 and WO2012/105893.

[0006] The prior art suggests several different approaches for introducing the light into the panel and for detecting the light downstream of the touch surface. For example, U.S. Pat. No. 7,432,893 proposes coupling light into the panel via revolved prisms that are attached to the rear surface of the panel, and detecting the light at photodetectors that are directly attached to the front surface of panel. In WO2010/064983, light is coupled into and out of the panel via the

edge surface that connects the front and rear surfaces of the panel, or via wedges that are attached to the front or rear surface of the panel. In WO2012/105893, a sheet-like microstructured element, e.g. a tape of light transmissive material, is provided on the front or rear surface of the panel for coupling light into and out of the panel.

[0007] One challenge when designing an optical touch system of this type is to enable consistent touch determination despite the fact that the detectors need to detect small changes in weak optical signals in presence of potentially significant interferences that affect the reliability of the optical signals. One such interference is caused by ambient light, e.g. from sunlight or residential lighting, that may impinge on the detectors and influence the optical signals. Another interference is caused by accumulation of contamination on the touch surface, such as fingerprints, drops of saliva, sweat, smear, liquid spills, etc. The contamination will interact with the propagating light and cause changes to the optical signals that may be difficult to distinguish from changes caused by “true objects”, e.g. objects that are actively manipulated in contact with the touch surface.

[0008] In touch-sensitive devices, there is also a general trend to avoid attaching components to the front surface. These components may form a frame around the touch-sensitive region and thereby reduce the ratio of the active area (the surface area that is available for touch interaction) to the total area of the touch-sensitive device. Furthermore, if the components protrude from the front surface of the panel, it may be necessary to provide a bezel at the perimeter of the panel to protect and hide the components and possibly any wiring connected to the components. Given the nature of user interaction with touch-sensitive devices, such a bezel may disrupt the user experience and even prevent certain types of interaction. The bezel may also cause dirt and other contaminants to accumulate in the area where the bezel joins the panel. To overcome this problem, it is desirable to design touch systems for flush mount of the panel in the supporting frame of the touch-sensitive device, i.e. such that the front surface of the panel is essentially level with the surrounding frame material. This is also known as “edge-to-edge”.

[0009] In aforesaid U.S. Pat. No. 7,432,893, the impact of ambient light is reduced by attaching the photodetectors to the front surface, such that the photodetectors face away from the ambient light that enters the panel through the front surface. This solution requires a significant bezel to hide and protect the photodetectors and the associated wiring. U.S. Pat. No. 7,432,893 also proposes to intermittently measure ambient levels at the photodetectors and compensate the respective projection measurement for the measured ambient level.

[0010] The influence of contamination may be handled by dedicated signal processing that actively estimates the influence of contamination over time and compensates for this influence, e.g. as disclosed in WO2011/028169, WO2011/049512 and WO2012/121652.

[0011] However, in view of the weak optical signals and small attenuation caused by touching objects, there is room for further improvement when it comes to increasing the robustness of the touch system to ambient light and contamination on the touch surface.

SUMMARY

[0012] It is an objective of the invention to at least partly overcome one or more of the above-identified limitations of the prior art.

[0013] Another objective is to provide a touch-sensitive apparatus that has a reduced sensitivity to ambient light.

[0014] A further objective is to provide a touch-sensitive apparatus that has a reduced sensitivity to contamination on the touch surface.

[0015] One or more of these objectives, as well as further objectives that may appear from the description below, are at least partly achieved by a touch-sensitive apparatus according to the independent claims, embodiments thereof being defined by the dependent claims.

[0016] A first aspect of the invention relates to a touch-sensitive apparatus, comprising: a light transmissive panel that defines a front surface and an opposite, rear surface; a plurality of light emitters optically connected to the panel so as to generate light that propagates by total internal reflection inside the panel across a touch-sensitive region on the panel; a plurality of light detectors optically connected to the panel so as to define a grid of propagation paths across the touch-sensitive region between pairs of light emitters and light detectors; wherein each of said light emitters is a VCSEL array, each said VCSEL array including a plurality of VCSELs driven in parallel to collectively form one light emitter.

[0017] In one embodiment each light detector is optically connected to the light transmissive panel via an angular filter which is applied to an outcoupling region of the light transmissive panel and is configured to transmit the propagating light only within a confined range of angles with respect to the normal of the outcoupling region; and wherein each light emitter (2) is optically connected to an incoupling region of the light transmissive panel and is configured to transmit a beam of light for total internal reflection so as to reach the outcoupling region at least partially within said confined range of angles.

[0018] In one embodiment a bandpass filter, tailored to an operating wavelength for said VCSELs, is arranged at said detectors.

[0019] In one embodiment said bandpass filter has a bandwidth of less than 5 nm.

[0020] In one embodiment the confined range extends from a lower angle limit θ_{min} to an upper angle limit θ_{max} , wherein the lower angle limit θ_{min} is equal to or larger than a critical angle θ_c , which is given by $\theta_c = \arcsin(1/n_{panel})$, with n_{panel} being the refractive index of the light transmissive panel at the outcoupling region.

[0021] In one embodiment said outcoupling region is arranged on at least one of the front and rear surfaces.

[0022] In one embodiment said incoupling region is arranged on at least one of the front and rear surfaces.

[0023] In one embodiment said incoupling region is arranged on a side edge of the panel, connecting the front and rear surfaces.

[0024] In one embodiment the lower angle limit θ_{min} exceeds the critical angle by an angle $\Delta\theta$, which is at least 5°, 10° or 15°.

[0025] In one embodiment the lower angle limit θ_{min} is equal to or larger than a first cut-off angle $\theta_w = \arcsin(n_w/n_{panel})$ with n being the refractive index of water, $n_{panel} > n_w$.

[0026] In one embodiment the lower angle limit θ_{min} is equal to or larger than a second cut-off angle $\theta_f = \arcsin(n_f/n_{panel})$, with n_f being the refractive index of finger fat, $n_{panel} > n_f$.

[0027] In one embodiment the angular filter (20) is configured as a dielectric multilayer structure.

[0028] In one embodiment the light transmissive panel (1) is mounted onto a front surface of a display device (34) by a lamination layer (36) of light transmissive material which is arranged in contact with the rear surface (6) of the light transmissive panel (1) and the front surface of the display device (34), and wherein the lower angle limit θ_{min} is equal to or larger than a laminate cut-off angle $\theta_{cl} = \arcsin(n_{lam}/n_{panel})$, with n_{lam} being the refractive index of lamination layer (36), $n_{lam} < n_{panel}$.

BRIEF DESCRIPTION OF DRAWINGS

[0029] Embodiments of the invention will now be described in more detail with reference to the accompanying schematic drawings.

[0030] FIG. 1 is a section view of a light transmissive panel to illustrate the principle of using TIR for touch detection.

[0031] FIG. 2A is a top plan view of a touch-sensitive apparatus according to an embodiment.

[0032] FIG. 2B is a 3D plot of an attenuation pattern generated based on energy signals from a TIR-based projection-type touch-sensitive apparatus.

[0033] FIG. 3A is section view of a VCSEL, illustrating its internal functional structure.

[0034] FIG. 3B is an elevated view of an emitter in the form of a VCSEL array.

[0035] FIG. 4 is a section view of a light outcoupling structure according to a first embodiment.

[0036] FIG. 5A is a plot of transmission as a function of incidence angle for an angular filter included in the first embodiment, and FIG. 5B is a perspective view of the range of angles that are transmitted by the angular filter.

[0037] FIG. 6 is a section view to illustrate characteristic angles of the angular filter and characteristic angles of the panel.

[0038] FIG. 7 is a section view to illustrate incoupling of ambient light via contamination on the touch surface.

[0039] FIG. 8 is a section view to illustrate a relation between bounce angles in a two-layer panel.

[0040] FIG. 9 is a section view to illustrate bounce angles in a panel which is laminated to a display device.

[0041] FIG. 10A is a section view of a light outcoupling structure according to a second embodiment.

[0042] FIGS. 10B-10C are section and plan views of a light outcoupling structure according to a third embodiment.

[0043] FIGS. 10D-10H are section views of variations of the first to third embodiments.

[0044] FIGS. 11A-11B are section and plan views of a first alternative outcoupling structure.

[0045] FIGS. 12A-12B are section and plan views of a second alternative outcoupling structure.

[0046] FIGS. 13A-13B are section and plan views of a light incoupling structure according to a first embodiment, and FIG. 13C is a section view of a variation of the first embodiment.

[0047] FIG. 14 is a bottom plan view of a sequence of structures arranged on a panel to couple light into and/or out of the panel.

[0048] FIG. 15 is a graph of light reflectivity at a panel-water interface as a function of angle of incidence inside the panel.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0049] In the following, various inventive light coupling structures will be presented as installed in an exemplifying TIR-based projection-type touch-sensitive apparatus. Throughout the description, the same reference numerals are used to identify corresponding elements.

[0050] FIG. 1 illustrates the concept of touch detection based on attenuation of propagating light, commonly denoted FTIR (Frustrated Total Internal Reflection). According to this concept, light is transmitted inside a panel 1 along a plurality of well-defined propagation paths. The panel 1 is made of solid material in one or more layers and may have any shape. The panel 1 defines an internal radiation propagation channel, in which light propagates by internal reflections, also denoted “bounces” in the following. In the example of FIG. 1, the propagation channel is defined between the boundary surfaces 5, 6 of the panel 1, and the front surface 5 allows the propagating light to interact with touching objects 7 and thereby defines the touch surface 4. The interaction is enabled by injecting the light into the panel 1 such that the light is reflected by total internal reflection (TIR) in the front surface 5 as it propagates through the panel 1. The light may be reflected by TIR in the rear surface 6 or against a reflective coating thereon. It is also conceivable that the propagation channel is spaced from the rear surface 6, e.g. if the panel comprises multiple layers of different materials. The panel 1 may thus be made of any solid material (or combination of materials) that transmits a sufficient amount of light in the relevant wavelength range to permit a sensible measurement of transmitted energy. Such material includes glass, poly(methyl methacrylate) (PMMA) and polycarbonates (PC). The panel 1 typically has a refractive index in the range of 1.3-1.7. For example, PMMA has a refractive index of about 1.5 and PC has a refractive index of about 1.6 in the near infrared (NIR). The panel 1 may be designed to be overlaid on or integrated into a display device or monitor (not shown).

[0051] As shown in FIG. 1, an object 7 that is brought into close vicinity of, or in contact with, the touch surface 4 may interact with the propagating light at the point of touch. In this interaction, part of the light may be scattered by the object 7, part of the light may be absorbed by the object 7, and part of the light may continue to propagate in its original direction across the panel 1. Thus, the touching object 7 causes a local attenuation or “frustration” of the total internal reflection, which leads to a decrease in the energy (or equivalently, the power or intensity) of the transmitted light, as indicated by the thinned lines downstream of the touching objects 7 in FIG. 1.

[0052] FIG. 2A illustrates an example embodiment of a touch-sensitive apparatus 100 that is based on the concept of FTIR. Emitters 2 are distributed along the perimeter of the touch surface 4, beneath the panel 1, to project light onto an incoupling structure on the panel 1 such that at least part of the light is captured inside the panel 1 for propagation by internal reflections in the propagation channel. Detectors 3 are distributed along the perimeter of the touch surface 4, beneath the panel 1, and are optically coupled to the panel 1 so as to receive part of the propagating light from a

respective outcoupling structure. The light from each emitter 2 will thereby propagate inside the panel 1 to a number of different detectors 3 on a plurality of light propagation paths D. Even if the light propagation paths D correspond to light that propagates by internal reflections inside the panel 1, the light propagation paths D may conceptually be represented as “detection lines” that extend across the touch surface 4 between pairs of emitters 2 and detectors 3, as indicated by dashed lines in FIG. 2A. Thus, the detection lines correspond to a projection of the propagation paths onto the touch surface 4. Thereby, the emitters 2 and detectors 3 collectively define a grid of detection lines (“detection grid”) on the touch surface 4, as seen in a top plan view. It is appreciated that FIG. 2A is an example, and that a (significantly) larger number of emitters 2 and/or detectors 3 may be included in the apparatus 100. Also, the distribution of emitters 2 and detectors 3 may differ.

[0053] The detectors 3 collectively provide an output signal, which is received and sampled by a signal processor 10. The output signal contains a number of sub-signals, also denoted “projection signals”, each representing the energy of light received by a certain light detector 3 from a certain light emitter 2. Depending on implementation, the signal processor 10 may need to process the output signal for separation of the individual projection signals. The projection signals represent the energy, intensity or power of light received by the detectors 3 on the individual detection lines D. Whenever an object touches a detection line, the received energy on this detection line is decreased or “attenuated”.

[0054] The signal processor 10 may be configured to process the projection signals so as to determine a property of the touching objects, such as a position (e.g. in the x,y coordinate system shown in FIG. 2A), a shape, or an area. This determination may involve a straight-forward triangulation based on the attenuated detection lines, e.g. as disclosed in U.S. Pat. No. 7,432,893 and WO2010/015408, or a more advanced processing to recreate a distribution of attenuation values (for simplicity, referred to as an “attenuation pattern”) across the touch surface 1, where each attenuation value represents a local degree of light attenuation. An example of such an attenuation pattern is given in the 3D plot of FIG. 2B, where the peaks of increased attenuation represent touching objects. The attenuation pattern may be further processed by the signal processor 10 or by a separate device (not shown) for determination of a position, shape or area of touching objects. The attenuation pattern may be generated e.g. by any available algorithm for image reconstruction based on projection signal values, including tomographic reconstruction methods such as Filtered Back Projection, FFT-based algorithms, ART (Algebraic Reconstruction Technique), SART (Simultaneous Algebraic Reconstruction Technique), etc. Alternatively, the attenuation pattern may be generated by adapting one or more basis functions and/or by statistical methods such as Bayesian inversion. Examples of such reconstruction functions designed for use in touch determination are found in WO2009/077962, WO2011/049511, WO2011/139213, WO2012/050510, and WO2013/062471, all of which are incorporated herein by reference.

[0055] In the illustrated example, the apparatus 100 also includes a controller 12 which is connected to selectively control the activation of the emitters 2 and, possibly, the readout of data from the detectors 3. Depending on implementation, the emitters 2 and/or detectors 3 may be activated

in sequence or concurrently, e.g. as disclosed in WO2010/064983. The signal processor **10** and the controller **12** may be configured as separate units, or they may be incorporated in a single unit. One or both of the signal processor **10** and the controller **12** may be at least partially implemented by software executed by a processing unit **14**, such as a CPU.

[0056] Embodiments of emitters and structures for incoupling of light will now be explained in detail with reference to FIGS. **3** and **13**. Generally, these embodiments are presented in the context of the touch-sensitive apparatus shown in FIG. **2A**.

[0057] One of the main challenges in the art of optical touch sensing is the need to obtain a usable optical signal at the detector side that is sufficiently strong or characteristic so as to be recognizable from background noise. The emitters **2** may generate light in any wavelength range, but FTIR systems preferably operate in the near infrared (NIR), i.e. at wavelengths of about 750 nm-1400 nm, which is also the range in which the following emitter **2** examples generate light. As mentioned, both ambient light and changes to propagating light caused by contamination on the touch surface are factors that must be taken into account. Rather than solely trying to shield the detector side of the touch-sensing system, the Applicant behind the present invention suggests that these problems can be alleviated by means of careful arrangement of the emitters **2**. While other types of light sources have been suggested, emitters **2** are generally provided by means of lasers, typically edge-emitting diode lasers, in state of the art FTIR systems. Such diode lasers have several benefits, in particular with regard to cost and availability. However, it has been noted that even with high power laser diodes, there is room for improvement in the signal to noise characteristics.

[0058] The present invention suggests providing emitters **2** in the form of VCSEL arrays. A VCSEL, Vertical Cavity Surface-Emitting Laser, is a semiconductor laser which is well known in the art of light sources as such, but which is significantly different from standard edge-emitting diode lasers. FIG. **3A** illustrates a typical VCSEL **21**, with reference to which the basic structure of this type of laser will be briefly described. It should be noted that VCSELs can be built differently, the design of FIG. **3A** being merely one example for the purpose of explaining the general function thereof. The layered structure is built up from a substrate **31**, typically a GaAs wafer, and the structure comprises a bottom mirror **33A**, a top mirror **33B**, with a laser cavity **35** in between. The mirrors **33A** and **33B** are created as a DBRs, Distributed Bragg Reflectors. The lower mirror **33A** is typically an n-type DBR, and has very high reflectivity for the laser wavelength, typically 99.9%, whereas the top mirror **33B** typically is a p-type DBR with about 99% reflectivity. This means that the illustrated embodiment is designed to be a top emitting VCSEL **21**. Alternatively, it is possible to construct a bottom emitting VCSEL, which provides light out through the substrate **31**. The laser cavity **35** comprises at least one quantum well structure, i.e. a single quantum well, or several repeated structures forming a multiple quantum well. A typical example of a single quantum well comprises two AlGaAs layers, with a thin GaAs layer in between in which quantum confinement is achieved. This is indicated in the drawing by a grey central layer of the laser cavity **35**. Also, oxide layers **37** are formed between the laser cavity **35** and the respective DBRs **33A** and **33B**. Each oxide layer **37** is typically shaped with a

circular aperture, which provides circular shaping of the laser beam that escapes through the top mirror **33B**. The laser is electrically fed by means of cooperating electrodes; e.g. a bottom electrode **39A** underneath the substrate **31**, and a top electrode **39B** for current injection. The top electrode **39B** has an aperture for allowing the laser light to escape, and is provided by means for current injection, such as by the illustrated bonding wire **39C**.

[0059] VCSELs have certain benefits compared to traditional edge-emitting lasers, such as low threshold current, circular beam shape with low divergence, and good temperature stability. Still, these characteristics have hitherto not made VCSELs preferable over edge-emitting laser diodes for FTIR emitter purposes. However, VCSELs have another benefit over edge-emitting lasers that can be utilized, they are possible to build into 2D (two-dimensional) arrays. This is possible since they are grown on the surface of a wafer, whereas a side-emitting laser is cut out from the wafer, making at best a one-dimensional array possible. Also, the Applicant has found that a VCSEL array provides an advantage as an emitter **2** for FTIR purposes, other than simply including several VCSELs in one package.

[0060] FIG. **3B** schematically shows an emitter **2** comprising a 2D VCSEL array, which in turn includes 9 individual VCSELs **21** in a 3x3 arrangement. Each VCSEL **21** may e.g. be of the type described with reference to FIG. **3A**. However, the specific details of the VCSELs **21** are not illustrated in FIG. **3B** for the sake of simplicity. All VCSELs **21** in the array are driven in parallel, i.e. the respective top electrode **39B** are interconnected. In one embodiment, indicated by the dashed overhead layer, a common conductive sheet **39D**, such as a metal layer, may be provided over the array structure with apertures for each VCSEL **21**, either so as to operate as a common top electrode, or connecting to the respective top electrodes **39B** of the individual VCSELs **21**. The 3x3 array illustrated in FIG. **3B** is merely an example to indicate the 2D displacement of the individual VCSELs **21**. In other embodiments, the emitter **2** may be formed of a 2D VCSEL array comprising hundreds of individual VCSELs **21**. The pitch between two individual VCSELs **21** may be as small as in the order of single μm or larger. It should be noted that the individual VCSELs of the array need not be dispersed in a Cartesian type grid as in FIG. **3B**. In other embodiments, the individual VCSELs may be arranged in a hexagonal grid, i.e. in parallel lines, each one offset half a pitch with respect to its neighboring lines. In yet another embodiment the individual VCSELs **21** may be arranged along concentric circles, or in other shapes. Regardless of the specific grid character, it may be realized that in the near field immediately over the emitter **2** the grid-like structure of the individual VCSELs **21** will characterize the irradiance over the field angle of the emitter **2**. However, the light beams **23** of the individual VCSELs **21** will blend within a very short distance to form an aggregate light beam of the emitter **2**. A benefit of the VCSEL array is a consequence of this aggregation, which with proper design may result in the unusual combination of a short coherence length and a narrow spectral bandwidth. The short coherence length results in reduced speckle noise at the detectors. Speckle patterns over the touch detection surface and in the detector plane otherwise tend to lead to speckle-induced noise. This is one of the reasons why the Applicant has found that a VCSEL array emitter **2** provides improved signal

readout for touch detection in FTIR systems over systems with a single laser emitter with corresponding power.

[0061] Also, a VCSEL array emitter 2 typically provides a light beam with a substantially circular cross-section with a narrow divergence of less than 20° ($1/e^2$), even down to 15° . Preferred embodiments further build on this fact, so as to improve signal detection at the detector 3 side, namely by restricting signal detection to a certain angular range with respect to an outcoupling area of the panel where the detector 3 is connected. Embodiments of structures for outcoupling and detection of light will now be explained in detail with reference to FIGS. 4-12. Generally, these embodiments are presented in the context of the touch-sensitive apparatus shown in FIG. 2A.

[0062] FIG. 4 illustrates a section that may be taken along any one of the detection lines D of the touch-sensitive apparatus in FIG. 2A. For simplicity, only a portion of the apparatus at and around the outcoupling structure is shown. The outcoupling structure is made up of a sheet-like angular filter 20 which is applied with its front face to the panel 1 at the periphery of the touch surface 4 to define an outcoupling port for the light propagating in the panel 1. A detector 3 is applied with its light-sensing surface 3A onto the rear face of the angular filter 20. In an alternative (not shown), a spacer of light transmissive material is disposed between the surface 3A and the filter 20. As used herein, the detector 3 may be any device capable of converting light, at least within a portion of the wavelength range that the emitter operates, into an electrical signal, such as a photo-detector, a CCD device, a CMOS device, etc. The angular filter 20 is designed to only be transmissive to light within a given angular range, i.e. for light that impinges on the filter 20 at certain angles of incidence to the normal N (FIG. 5B) of the filter 20. FIG. 5A is a plot of the transmission of the filter 20 as a function of angle of incidence. As seen, the filter 20 transmits light within a given angular range between a lower limit θ_{min} and an upper limit θ_{max} , while reflecting light that impinges on the filter at other angles of incidence. Any criterion may be used for defining the limits θ_{min} , θ_{max} , e.g. a percentage (e.g. 25, 50 or 75) of absolute or maximum transmission. FIG. 5B illustrates the angular range in relation to a single position on the front surface of the filter 20. As seen, the angular range is equal in all directions in the plane of the filter 20. Preferably, the angular range is essentially the same at all positions on the filter 20.

[0063] The filter 20 may be designed as a dielectric multilayer structure of at least two different materials, similar to an interference filter. It lies within the reach of the person skilled in optical design to select appropriate materials and number of layers to achieve the desired angular range for light at a wavelength generated by the emitters 2. As an example, the article "Injecting Light of High-Power LEDs into Thin Light Guides", by Cornelissen et al, published in Proc. SPIE 7652, International Optical Design Conference 2010, pp 7652121-7652126, 2010, discusses optical coupling in a backlight light guide. A dielectric multilayer filter is deposited on the bottom of the light guide panel, and the top surface of a LED for injecting light into the light guide is optically coupled to the filter by a silicone adhesive. The filter is optimized to only transmit light emitted from the LED at angles larger than the critical angle at the light guide-air interface. The purpose of the multilayer is thus to only transmit light that can propagate in the light guide. The light emitted at smaller angles is reflected back

toward the rough LED surface where it is subsequently recycled by reflection and redistribution. Further elaboration on this incoupling approach is given in the article "Dielectric multilayer angular filters for coupling LEDs to thin light guides", by Mu et al, published in Proc. SPIE 8170, pp 8170011-81700110, 2011.

[0064] It should be understood that the filter 20 need not be designed to define the given angular range for all wavelengths, but only for a limited wavelength range that includes the wavelength(s) of the propagating light. In a preferred embodiment, the angular filter 20 is reflective to all angles outside the limited wavelength range, or at least a range that is otherwise difficult to block with standard off the shelf daylight filters or dyes normally incorporated in detector packages. The filter may actually be constructed having a carrier layer that is dyed or simply an ink jet painted thin layer in order to simplify the multilevel design. Standard IR inks block effectively in the visible area while transmitting over e.g. 750 nm. In this aspect, the use of a VCSEL array as emitter 2 provides an additional benefit, since it is very narrow light source. Typically, a VCSEL is a single mode laser, and a VCSEL array emitter 2 may have a spectral width of <1 nm FWHM (Full Width at Half Maximum). In addition, a VCSEL exhibits high temperature stability, with very little drift of <0.1 nm/deg. It is thereby possible to have a very narrow band pass filter of less than 5 nm. This way it is possible to block out virtually all ambient light outside the spectral range of the emitter, by means of an appropriate band pass filter, which may significantly increase the signal to noise ratio at the detector side. Such a band pass filter function may be arranged in the angular filter 20 by means of the structure and material choice of said dielectric layers in the filter 20. Alternatively, the band pass filter function may be provided as a separate element in addition to the angular filter 20, e.g. if the angular filter is of a more mechanically vignetting nature as described below with reference to FIGS. 11 and 12.

[0065] It should also be understood that the filter 20 is designed to provide the angular range $[\theta_{min}-\theta_{max}]$ for a specific installation, i.e. when mounted with its front face to the panel 1 and with its rear side to the surface 3A (or a spacer). For example, the design may be adapted to the refractive index of the panel 1 and the refractive index of the light-sensing surface 3A (or the spacer).

[0066] In embodiments of the invention, the filter 20 is tailored to suppress the amount of ambient light received at the light-sensing surface 3A in relation to the amount of useful light, i.e. light that has propagated on one or more detection lines from a respective incoupling structure. This effect may be achieved by adapting the angular range of the filter 20 to the angles of incidence (AOI) of the propagating light on the filter 20. Ambient light typically contains daylight and/or light from artificial light sources. Such ambient light includes NIR light which, if it falls on the surface 3A, will interfere with the detection of the propagating NIR light inside the panel 1. As exemplified by ray A1 shown in FIG. 4, ambient light that falls on the front surface 5 is refracted into the panel 1 and would have impinged on the surface 3A were it not for the angular filter 20. The angular filter 20 is designed to reflect the ambient light A1 back towards the front surface 5. Ambient light that falls onto the touch surface 4 at other areas than over the detector 3 will, irrespective of its angle to the touch surface 4, be transmitted through the panel 1, as exemplified by ray A2.

The ambient light will not be captured by TIR in the panel 1 since it cannot be refracted into the panel 1 at an angle larger than the critical angle (see below). As exemplified by ray P1, light that propagates in the panel 1 by TIR and strikes the filter at an AOI within the angular range of the filter 20, is transmitted to the light-sensing surface 3A. FIG. 4 also indicates a ray P2 that propagates in the panel 1 by TIR and strikes the filter 20 at a smaller AOI, which is outside the angular range of the filter 20. This ray P2 is reflected by the filter 20. However, with an emitter 2 in the form of a narrow beam VCSEL array, and careful design of the filter 20, a substantial amount of light injected from the emitter 2 may be used for detection by the detector 3. In other words, very few, if any, rays of light emanating from the emitter 2 will propagate like ray P2 of FIG. 4. Preferably, the filter 20 is configured to let through light to the detector 3 within an angular range which is tailored to the beam divergence of the VCSEL array emitter 2. It should be noted that a beam divergence of e.g. 19° ($1/e^2$), such as offered in VCSEL arrays provided by Princeton Optonics Inc., translates to about 12.5° ($1/e^2$) in a panel with a refractive index of 1.5. It can thereby be understood that it is possible to make use of a very narrow angular filter, virtually without sacrificing or losing any emitter light. The use of an angular filter 20 in combination with a VCSEL array emitter 2 thus provides a simple technique for selecting the light that is passed to the detector 3 to be represented in the projection signals. To achieve even better performance with a very narrow angular filter it may be suitable to use e.g. wafer level optics in order to collimate the theta range even further.

[0067] The present Applicant has realized that advantageous technical effects may be achieved by careful selection of the lower limit θ_{min} of the filter 20. FIG. 6 illustrates, in section view, a portion of the panel 1, where different characteristic angles of the panel 1, as well as the limits θ_{min} , θ_{max} of the filter 20, are mapped to a position on the front surface 5. In this example, it is assumed that the panel 1 is made of a single material and has the same refractive index n_{panel} at the front and rear surfaces 5, 6. All angles are defined with respect to the normal N of the front surface 5.

[0068] FIG. 6 indicates the critical angle θ_c , which is given by $\theta_c = \arcsin(1/n_{panel})$ and is the minimum AOI of the light that propagates by TIR between the surfaces 5, 6. FIG. 6 also indicates a cut-off angle θ_w for interaction between the propagating light and water deposited on the front surface 5. Propagating light that strikes the surface 5 at AOIs below θ_w will be partly coupled out of the panel 1 and into water on the surface 5, whereas propagating light at AOIs above θ_w will be totally reflected at the interface between the surface 5 and water. According to Snell's law: $n_{panel} \sin(\theta_w) = n_w \sin(90^\circ)$, which yields $\theta_w = \arcsin(n_w/n_{panel})$, where the refractive index of water, n_w , is in the range 1.31-1.34, depending on temperature, wavelength, salt content, etc. In the following examples, it is assumed that $n_w = 1.33$. FIG. 6 also indicates a cut-off angle θ_f for interaction between the propagating light and finger fat deposited on the front surface 5. Propagating light that strikes the surface 5 at AOIs below θ_f will be partly coupled out of the panel 1 and into finger fat on the surface 5, whereas propagating light at AOIs above θ_f will be totally reflected at the interface between the surface 5 and finger fat. According to Snell's law: $n_{panel} \sin(\theta_f) = n_f \sin(90^\circ)$, which yields $\theta_f = \arcsin(n_f/n_{panel})$, where the refractive index of finger fat, n_f , is in the range of 1.36-1.48, depending on temperature, wavelength, composition, etc. In

the following examples, it is assumed that $n_f = 1.45$. In the example of a panel made of PMMA with $n_{panel} = 1.49$, this approximately yields $\theta_c = 42^\circ$, $\theta_w = 63^\circ$, and $\theta_f = 77^\circ$.

[0069] In one embodiment, the angular range is set to $\theta_{min} \approx \theta_c < \theta_{max} < 90^\circ$. This will ensure that all propagating light reaches the light-sensing surface 3A while preventing a major part of the ambient light from striking the light-sensing surface 3A.

[0070] Further suppression of interferences, i.e. unwanted signal components at the light-sensing surface 3A, may be achieved by setting θ_{min} to exceed θ_c .

[0071] In one such embodiment, the angular range is set to $\theta_{min} = \theta_c + \Delta\theta < \theta_{max} < 90^\circ$, with $\Delta\theta$ equal to, or larger than, e.g. 5° , 10° or 15° . This embodiment has been found to significantly reduce the influence of ambient light that is coupled into the panel 1 through deposits on the touch surface 4, such as water, saliva, fingerprints, smear, etc. (collectively denoted "contamination" herein). It will also help suppressing other forwards dominated scattering factors (Mie type) e.g. from surface treatments such as antiglare and bulk scattering. With reference to ray A2 in FIG. 4, it was mentioned that all ambient light that falls onto the touch surface 4 will pass through the panel 1. However, the present Applicant has found that this is only true for a perfectly clean touch surface 4. As indicated in FIG. 7, contamination 30 on the touch surface 4 may allow ambient light at an angle of incidence near or larger than θ_c to leak into the panel 1 and be trapped by TIR therein. The present Applicant has realized that this ambient light may have a sizeable influence on the measured signal levels at the detector 3. The Applicant has also found, surprisingly, that the trapped ambient light is largely concentrated to a limited range of AOIs at the filter 20, close to and above the critical angle θ_c . Thus, the trapped ambient light can be prevented from reaching the detector 3 by choosing $\theta_{min} = \theta_c + \Delta\theta$ with an angular span $\Delta\theta$ equal to or larger than the limited range of AOIs. It is currently believed that the concentration of the ambient light to the limited range of AOIs is caused by Mie scattering in the contamination 30, as well as refraction by contamination droplets, causing the ambient light to enter the panel with a slightly widened distribution, as indicated by 32 in FIG. 7. The widening due to Mie scattering and refraction in contamination droplets may be in the range of $\pm 5^\circ$ to $\pm 10^\circ$. The ambient light typically falls onto the contamination 30 at many different angles. Since all ambient light that enters the panel 1 at an angle below θ_c will pass through the panel 1 and since the intensity of the ambient light typically decreases with increasing angle to the normal N of the panel, the trapped ambient light will be concentrated at and slightly above θ_c . It should also be noted that if the refractive index of the panel 1 is larger than the refractive index of the contamination 30: $n_{panel} > n_{cont}$, the AOIs for the ambient light refracted into the panel 1 via the contamination 30 cannot exceed $\arcsin(n_{cont}/n_{panel})$.

[0072] The present Applicant has found that further advantageous and unexpected effects are achieved by designing the filter 20 with a given relation between the lower limit θ_{min} and the cut-off angle θ_w or θ_f .

[0073] In one such embodiment, the angular range is set to $\theta_{min} \leq \theta_{max}$ where $\theta_{min} \geq \theta_w$ and $\theta_{max} < 90^\circ$. Thus, the filter 20 is designed to only transmit light with AOIs that are equal to or larger than the cut-off angle θ_w for water. This embodiment has the ability of significantly reducing the influence on the resulting projection signals from water-containing

deposits on the touch surface **4**. As noted above, the portion of the propagating light that strikes water at AOIs below θ_w will be at least partially coupled out of the panel **1** and interact with the water. Thus, the portion of the propagating light that reaches the filter **20** at AOIs below θ_w has been significantly more attenuated by water than the remainder of the propagating light. This embodiment also has the ability of reducing the impact of differences in finger interaction between users and even between fingers of a single user. These differences may make it difficult to properly detect all touching objects on the touch surface, and it may require the signal processor **10** to be configured with a large dynamic range for retrieving and processing the projection signals. A significant part of the differences in finger interaction has been found to emanate from different moisture levels on the fingers. The filter design of this embodiment will suppress the influence of moisture in the projection signals and thus reduce the impact of differences in finger interaction.

[0074] In this embodiment, the propagating light that is transmitted by the filter **20** has impinged on the touch surface **4** with AOIs at or above θ_w . At these AOIs, the propagating light will still be coupled into the outermost layer of the finger that form part of the epidermis, since this layer (stratum corneum) is known to have a refractive index of about 1.55 in the near infrared (NIR), e.g. according to measurement results presented in “A survey of some fundamental aspects of the absorption and reflection of light by tissue”, by R. J. Scheuplein, published in J. soc. cos. CHEM. 15, 111-122 (1964), and “The optics of human skin”, by Anderson and Parrish, published in Journal of Investigative Dermatology 77, 1, 13-19 (1981). This means that propagating light is coupled into the finger for AOIs at least up to a cutoff angle $\theta_{cs} = \arcsin(1.55/n_{panel})$. If $n_{panel} < 1.55$, the cutoff angle θ_{cs} is not relevant, and all AOIs below 90° will interact with the stratum corneum (and other outer layers of the finger). If $n_{panel} > 1.55$, it is conceivable to set $\theta_{max} \leq \theta_{cs}$ for the filter **20**, should there be a need to suppress propagating light at AOIs above θ_{cs} .

[0075] It should also be noted that this embodiment fully eliminates ambient light that has been coupled into the panel via water on the touch surface **4** and has propagated by TIR to the filter **20**. As explained above, this ambient light has a maximum AOI of $\arcsin(n_{cont}/n_{panel})$ which is equal to θ_w with $n_{cont} = n_w$.

[0076] In another embodiment, the angular range is set to $\theta_{min} \leq \theta \leq \theta_{max}$, where $\theta_{min} \geq \theta_f$ and $\theta_{max} < 90^\circ$. This embodiment has the ability of significantly reducing the influence on the resulting projection signals from deposits containing finger fat, e.g. fingerprints, on the touch surface **4**. Fingerprints is typically a substantial part of the contamination on the touch surface, and is a major concern when processing the projection signals for detecting the touching objects. It is thus a significant technical achievement to be able to suppress the influence of fingerprints, and it will reduce the requirements on the signal processor **10** to track and compensate for contaminations. This embodiment also has the ability of further reducing the impact of differences in finger interaction, since it suppresses the interaction caused by fat on the fingers. Furthermore, this embodiment fully eliminates ambient light that has been coupled into the panel via finger fat on the touch surface **4** and has propagated by TIR to the filter **20**. This ambient light has a maximum AOI of $\arcsin(n_{cont}/n_{panel})$ which is equal to θ_f with $n_{cont} = n_f$.

[0077] Reverting to FIG. 4, the width W of the filter **20** (in the direction of the respective detection line) may be optimized with respect to the range of AOIs of the propagating light that should be transmitted onto the light-sensing surface **3A**. To ensure that all of this propagating light (i.e. the light with appropriate AOIs) strikes the filter at least once, the width W may be set to exceed the relevant minimum distance between bounces in the rear surface (“minimum bounce distance”). If the panel is made of a single material, the minimum bounce distance is given by $2 \cdot t \cdot \tan(\theta_{min})$, where t is the thickness of the panel **1**. To achieve a consistent detection of the propagating light within the limits $\theta_{min}, \theta_{max}$, it may be desirable to set the width to exceed the relevant maximum distance between bounces in the rear surface (“maximum bounce distance”). If the panel is made of a single material, the maximum bounce distance is given by $2 \cdot t \cdot \tan(\theta_{max})$. In practice, the width W may be given by other design considerations, which may (but need not) set the limit θ_{max} of the filter **20**. Further, the skilled person is able to calculate the minimum bounce distance and the maximum bounce distance for a panel consisting of more than one layer.

[0078] The foregoing design rules for the angular filter were given for a panel **1** with a single index of refraction. However, corresponding design rules are applicable for the angular filter **20** when applied to a panel **1** made up of two or more layers with different index of refraction. FIG. 8 illustrates a panel **1** formed by a top layer with index of refraction n_1 and a bottom layer with index of refraction n_2 . Light having an angle of incidence θ_1 at the front surface **5** will impinge on the rear surface **6** with an angle of incidence $\theta_2 = \arcsin(n_1/n_2 \sin(\theta_1))$. This means that the limits $\theta_{min}, \theta_{max}$ of the filter **20**, if mounted on the rear surface **6**, should be set with respect to the critical angle θ_c at the front surface **5** as represented at the rear surface **6**, or with respect to the cut-off angles θ_w, θ_f at the front surface **5** as represented at the rear surface **6**. The skilled person realizes that n_{panel} in the above expressions for θ_c, θ_w and θ_f is the refractive index of the panel **1** at the outcoupling region where the filter is mounted. In the example of FIG. 8, $n_{panel} = n_2$.

[0079] A different situation may arise if the panel **1** is laminated to a display **34** by means of a lamination layer **36**, as shown in FIG. 9. If the display **34** does not reflect light back to the panel **1**, the lamination layer **36** may be designed with a smaller refractive index n_{lam} than the panel. This will cause light that impinges on the interface between the panel and the lamination layer **36** at angles equal to $\theta_{c,l} = \arcsin(n_{lam}/n_{panel})$, or larger, to be totally reflected at this interface. Light that impinges on the interface at smaller angles, e.g. as indicated by a dotted arrow in FIG. 9, will be transmitted via the lamination layer **36** to the display **34**. This means that the minimum AOI of the light that propagates by TIR between the surfaces **5, 6** and strikes the filter **20**, is $\theta_{c,l}$ rather than θ_c . In such an embodiment the angular range of the filter **20** may be set according to $\theta_{min} \leq \theta \leq \theta_{max}$, where $\theta_{min} \geq \theta_{c,l}$ and $\theta_{max} < 90^\circ$. Of course, the angular range may instead be designed with respect to θ_w or θ_f according to the embodiments described above.

[0080] It should be noted that a lamination layer **36** may generally be introduced between the rear surface **6** of the panel **1** and any external device when it is desirable to “optically isolate” the propagating light in panel from the external device, whereby the propagating light is shifted to larger angles of incidence by virtue of $\theta_{c,l} > 0$. Based on the

foregoing discussion, it is understood that it may be desirable to select the material of the lamination layer 36 such that $\theta_{c,i} \geq \theta_w$ or $\theta_{c,i} \geq \theta_f$, so as to reduce the attenuation caused by contamination on the touch surface 4. In another variant, it may be desirable to select the material of the lamination layer 36 such that $\theta_{c,i} \geq \theta_c + \Delta\theta$, where $\Delta\theta$ is selected to reduce the influence of ambient light that enters the panel via contamination on the touch surface 4, as discussed above with reference to FIG. 7. For efficient utilization of light, the light emitters 2 may be coupled to the panel 1 such that the injected light impinges on the lamination layer 36 at an AOI that exceeds $\theta_{c,i}$, to avoid that useful light is leaked into the lamination layer 36. The concept of using a lamination layer 36 for reducing the impact of ambient light or contamination may, but need not, be used in combination with an angular filter in the outcoupling structure and/or an angular filter in the incoupling structure (see below).

[0081] In the foregoing, it has been assumed that the cutoff angles θ_w and θ_f are given by the TIR angle at the interface between the panel and water and finger fat, respectively. However, it shall be appreciated that the TIR angles correspond to 100% reflection at the interface, and that the reflectivity at the interface does not exhibit a step change at the TIR angle but is a continuous, but steep, function within increasing AOI until the TIR angle. This is illustrated in FIG. 15, which is a graph of the reflectivity R for unpolarised light at a panel-to-water interface as a function of AOI, θ , given by the equations:

$$R_p = \frac{\left| n_{panel} \cos \theta - n_w \sqrt{1 - \left(\frac{n_{panel}}{n_w} \sin \theta \right)^2} \right|^2}{\left| n_{panel} \cos \theta + n_w \sqrt{1 - \left(\frac{n_{panel}}{n_w} \sin \theta \right)^2} \right|^2}$$

$$R_s = \frac{\left| n_{panel} \sqrt{1 - \left(\frac{n_{panel}}{n_w} \sin \theta \right)^2} - n_w \cos \theta \right|^2}{\left| n_{panel} \sqrt{1 - \left(\frac{n_{panel}}{n_w} \sin \theta \right)^2} + n_w \cos \theta \right|^2}$$

$$R = \frac{R_s + R_p}{2}$$

[0082] with $n_{panel}=1.51$ and $n_w=1.33$.

[0083] As understood from FIG. 15, it is possible to define the cutoff angles θ_w and θ_f at a given fraction of 100% reflection, e.g. 0.25 or 0.50, while still achieving an essentially complete suppression of the influence of water and finger fat, respectively. In practice, this means that it is possible to adjust the cutoff angles slightly from the TIR angles towards smaller AOIs: $\theta_w = \arcsin(n_w/n_{panel}) - \delta\theta$ and $\theta_f = \arcsin(n_f/n_{panel}) - \delta\theta$, where $\delta\theta$ is typically less than 2°. As used herein, any reference to θ_w and θ_f is intended to inherently include this minor shift $\delta\theta$.

[0084] Generally, it may be desirable to limit the size of the individual detectors 3, and specifically the extent of the light-sensing surface 3A. For example, the cost of light detectors may increase with size. Also, a larger detector typically has a larger capacitance, which may lead to slower response (longer rise and fall times) of the detector. It is realized that it may be difficult to reduce the extent W of the detector 3 in the embodiment of FIG. 4, without sacrificing the ability to consistently detect the propagating light.

[0085] FIG. 10A illustrates an alternative embodiment that at least partly overcomes this problem. Like in FIG. 4, the angular filter 20 is applied to the rear surface 6, but the detector 3 is arranged with its light-sensing surface 3A essentially perpendicular to the main extent of the panel 1. As used herein, “essentially perpendicular” is intended to include deviations of about $\pm 20^\circ$ or less from perpendicular. A spacer 22 is disposed between the angular filter 20 and the light-sensing surface 3A. The spacer 22 may be made of any suitable light transmissive material, such a plastic material or glass, or a silicone compound, a glue, a gel, etc. In the example of FIG. 10A, the spacer 22 is made of the same material as the panel 1, i.e. $n_{spacer}=n_{panel}$. By arranging the surface 3A vertically, the extent of the surface 3A may be reduced significantly compared to the embodiment in FIG. 4. When the extent of the angular filter is W, the minimum vertical extent of the surface 3A may be given by $W/\tan(\theta_{min})$ to ensure that all of the transmitted light from the filter 20 is received at the surface 3A. The extent of the surface 3A may be reduced further by selecting the material of the spacer 22 such that $n_{spacer} < n_{panel}$, causing the transmitted light to be refracted away from the normal and resulting in a smaller projected height at the location of the surface 3A.

[0086] Even if the outcoupling structure in FIG. 10A allows for a smaller light-sensing surface 3A, the extent of the surface 3A is still dependent on the angular range of the filter 20. Further, the vertical extent of the surface 3A has a direct impact on the thickness of the apparatus 100. At present, the embodiment in FIG. 10A is believed to be useful only when θ_{min} is larger than about 45° , to avoid that the height of the outcoupling structure becomes excessive.

[0087] This problem is at least partly overcome by the embodiment illustrated in FIGS. 10B-10C. As shown in section in FIG. 10B, the angular filter 20 is applied to the rear surface 6, and a light recycler 40 is arranged beneath the filter 20 in surrounding relationship to the light-sensing surface 3A. The recycler 40 is designed to internally reflect the light that is transmitted by the filter 20 and to modify the angular distribution of the transmitted light. The recycler 40 defines a reflective enclosure around the light-sensing surface 3A. The enclosure is filled by a spacer material 22, e.g. any of the spacer materials discussed in relation to FIG. 10A. The recycler 40 comprises a reflective bottom surface 42A with an opening for the detector 3 (illustrated as mounted on a PCB 45) and reflective sidewalls 42B that extend from the bottom surface 42A to the filter 20. In the illustrated embodiment, the bottom surface 42A is diffusively reflective to impinging light, whereas the sidewalls 42B are specularly reflective to impinging light. As used herein, “specular reflection” is given its ordinary meaning, which refers to the mirror-like reflection of light from a surface, in which light from a single incoming direction (a ray) is reflected into a single outgoing direction. Specular reflection is described by the law of reflection, which states that the direction of incoming light (the incident ray), and the direction of outgoing light reflected (the reflected ray) make the same angle with respect to the surface normal, and that the incident, normal, and reflected directions are coplanar. As used herein, “diffuse reflection” is given its ordinary meaning, which refers to reflection of light from a surface such that an incident ray is reflected at many angles rather than at just one angle as in specular reflection. The diffuse reflection is also known as “scattering”. The skilled person appreciates that many surfaces/elements/materials exhibit a combination

of specular and diffuse reflection. As used herein, a surface is considered “diffusively reflective” when at least 20% of the reflected light is diffuse. The relation between diffuse and specular reflection is a measurable property of all surfaces/elements/materials.

[0088] To exemplify the function of the outcoupling structure, FIG. 10B illustrates a single ray P1 that is transmitted and refracted into the recycler 40 by the filter 20. The ray strikes the bottom wall 42A and is diffusively reflected, as indicated by the encircled rays 46. The diffusively reflected light spreads over a large solid angle in the recycler 40, and some of this light is specularly reflected by the filter 20 onto the light-sensing surface 3A. Although not shown, other parts of the diffusively reflected light is likely to undergo further reflections in the recycler 40, against the sidewalls 42B, the angular filter 20 and the bottom wall 42A, and eventually impinge on the surface 3A. It should be noted that the angular filter 20 will also transmit light from the recycler 40 back into the panel 1, specifically light that has an angle of incidence within a given angular range which may, but need not, be identical to the angular range $[\theta_{min}-\theta_{max}]$. If these angular ranges are identical, or at least substantially overlapping, it is necessary to redistribute the light by diffuse reflection inside the recycler 40 to prevent that the light that enters the recycler 40 from the panel 1 escapes back into the panel 1 via the filter 20.

[0089] In the embodiment of FIG. 10B, the use of specular side walls 42B ensures that all of the light that enters the recycler 40 via the filter 20 is re-directed by specular reflection(s) towards the bottom of the recycler 40, where it is either redistributed by diffuse reflection in the bottom wall 42A or directly received by the light-sensing surface 3A. The diffusively reflected light is typically, but not necessarily, emitted with a main direction that is perpendicular to the bottom wall 42A, as shown in FIG. 10B. The bottom wall 42A may e.g. be a near-Lambertian diffuser. The use of a planar bottom wall 42A, as in FIG. 10B, ensures that most of the diffusively reflected light hits the filter 20 at AOIs outside the angular range, such that main portion of the diffusively reflected light is reflected by the filter 20 back into the recycler 40.

[0090] In an alternative, both the bottom wall 42A and the side walls 42B are diffusively reflective. In another alternative, the side walls 42B are diffusively reflective, while the bottom surface 42A is specularly reflective. In all embodiments, it is possible that only a part of the bottom wall 42A and/or the side walls 42B is diffusively reflective. Generally, it may be advantageous to provide diffusive scattering on surfaces that are arranged such that a significant portion of the light impinging on these surfaces would otherwise be specularly reflected onto the filter 20 within the angular range.

[0091] In yet another alternative, the bottom wall 42A is not specularly or diffusively reflective, but provided with a micro-structure, which is configured to reflect and re-direct impinging light onto the light sensing-surface 3A, by specular reflection against the filter 20 and possibly by reflection against the specular side walls 42B. The micro-structure thus forms a mirror with an optical power that is tailored to the incoming light, i.e. the light that is transmitted by the filter 20 and hits the micro-structure on the bottom wall 42A, either directly or by reflection(s) in the side walls 42B. The use of specularly reflective side walls 42B may facilitate the design of the micro-structure, but it is possible to use

diffusively reflective side walls 42B, or a combination thereof. The micro-structure may be implemented as a sheet-like Fresnel mirror.

[0092] Compared to the embodiments in FIG. 4 and FIG. 10A, there is no direct relation between the extent of the angular filter 20 and the required size of the light-sensing surface 3A, since the recycler 40 is designed to retain a portion of the transmitted light by internal reflections until it impinges on the surface 3A. Furthermore, there is large freedom of placing the detector 3 in relation to the recycler 40, and it can even be accommodated in a side wall 42B instead of the bottom wall 42A. It is realized that the outcoupling structure may be optimized with respect to manufacturing requirements, without any major loss in outcoupling efficiency. Also, assembly tolerances may be relaxed.

[0093] As shown in the plan view of FIG. 10C, the combination of angular filter 20 and recycler 40 will collect light from all directions in the plane of the panel 1, provided that the incoming light impinges on the angular filter 20 with AOIs within the angular range $[\theta_{min}-\theta_{max}]$. Thus, the outcoupling structure in FIG. 10C can accept light from many different directions in the plane of the panel 1 and define the end point of detection lines from different emitters (cf. FIG. 2A). In the example of FIG. 10C, the recycler 40 is circular in plan view, but other shapes are possible, e.g. elliptical or polygonal. As described in relation to FIG. 4, it may be desirable that the extent W of the recycler along each of the detection lines is equal to at least the minimum bounce distance or at least the maximum bounce distance.

[0094] In all embodiments, the specularly reflective wall (s) of the recycler 40, if present, may be implemented by an external coating, layer or film which is applied to the spacer material 22, e.g. a metal such as aluminum, copper or silver, or a multilayer structure, as is well-known to the skilled person.

[0095] In all embodiments, the diffusively reflective wall (s) of the recycler 40, if present, may be implemented by an external coating, layer or film of diffusively reflective material which is applied to the spacer material 22. In one implementation, the diffusively reflective material is a matte white paint or ink. In order to achieve a high diffuse reflectivity, it may be preferable for the paint/ink to contain pigments with high refractive index. One such pigment is TiO_2 , which has a refractive index $n=2.5-2.7$. It may also be desirable, e.g. to reduce Fresnel losses, for the refractive index of the paint binder (vehicle) to match the refractive index of the spacer 22. For example, depending on refractive index, a range of vehicles are available such as oxidizing soya alkyds, tung oil, acrylic resin, vinyl resin and polyvinyl acetate resin. The properties of the paint may be further improved by use of e.g. EVOQUE™ Pre-Composite Polymer Technology provided by the Dow Chemical Company. There are many other diffusively reflective coating materials that are commercially available, e.g. the fluoropolymer Spectralon, polyurethane enamel, barium-sulphate-based paints or solutions, granular PTFE, microporous polyester, Makrofol® polycarbonate films, GORE® Diffuse Reflector Product, etc. Also, white paper may be used. Alternatively, the diffusively reflective material may be a so-called engineered diffuser. Examples of engineered diffusers include holographic diffusers, such as so-called LSD films provided by the company Luminit LLC.

[0096] According to other alternatives, the diffusively reflective wall(s) of the recycler 40 may be implemented as a micro-structure in the spacer material 22 with an overlying coating of specularly reflective material. The micro-structure may e.g. be provided in the spacer material 22 by etching, embossing, molding, abrasive blasting, etc. Alternatively, the micro-structure may be attached as a film or sheet onto the spacer material 22. The above-described mirror with an optical power tailored to incoming light may also be provided as a micro-structure in or on the spacer material 22.

[0097] Below follows a description on variants of the outcoupling structure in FIG. 4. Unless explicitly excluded, the bottom wall 42A and the side walls 42B may be configured according to any of the embodiments, alternatives and variants described in relation to FIGS. 10B-10C.

[0098] FIG. 10D illustrates an outcoupling structure that may improve the ability of the outcoupling structure to achieve a consistent detection of the propagating light within the limits θ_{min} , θ_{max} when the width W of the angular filter 20 and the light-sensing surface 3A is smaller than the maximum bounce distance or even smaller than the minimum bounce distance. This is achieved by providing the edge surface, which connects the front and rear surfaces 5, 6, with a specularly reflective coating 48 at the location of angular filter 20. As shown, the coating 48 will operate to reflect, back into the panel 1, the propagating light that passes above the angular filter 20, including propagating light that strikes the filter 20 at AOIs outside the angular range $\theta_{min}-\theta_{max}$ and propagating light that does not strike the angular filter 20. It is realized that the coating 48 will reflect the incoming light without changing its AOIs. Thus, a portion of the reflected light will have AOIs that fall within the angular range of the filter 20. Such reflected light will be transmitted by the filter 20 to the extent that it strikes the filter 20 on its way back towards the touch surface 4. Thereby, the reflective coating 48 operates to increase the outcoupling efficiency.

[0099] It is not strictly necessary to arrange the angular filter 20 directly adjacent to the edge surface for the coating 48 to perform its function of increasing outcoupling efficiency. However, such a placement may be preferred to ensure that light on different detection lines can be reflected by the coating 48 onto the angular filter 20.

[0100] The reflective coating 48 may also be implemented to increase outcoupling efficiency in the embodiment of FIGS. 10B-10C.

[0101] FIG. 10E illustrates a variant of the outcoupling structure in FIG. 10B. The recycler 40 is configured as a hollow case, i.e. without spacer material. This is achieved by providing the angular filter 20 with a diffusively transmitting element 52 on its exit surface, such that the light that enters the recycler is diffusive. Since light is angularly redistributed on entry, the walls 42A, 42B may, but need not, be specularly reflective.

[0102] FIG. 10F illustrates a further variant of the outcoupling structure in FIG. 10B. Here, the detector 3 is side-looking when mounted on a PCB 45. The detector 3 is inserted into the spacing material 22 such that the light-sensing surface 3A projects beyond the bottom surface 42A of the recycler 40 and is perpendicular to the extent of the panel 1 and the angular filter 20. By arranging a side-looking detector 3 inside the recycler 40, it is possible to provide an increased light-sensing surface 3A for a given opening in

bottom surface 42A, especially if the light-sensing surface 3A extends around the perimeter of the detector 3. The increased light-sensing surface 3A may result in an increased outcoupling efficiency. In a variant, the top surface of the detector 3 may be provided with a diffusively reflective structure to enhance the angular redistribution of light inside the recycler 40.

[0103] FIG. 10G illustrates a further variant of the outcoupling structure in FIG. 10B, in which the recycler 40 is configured as a funnel tailored to direct the light transmitted by the filter 20 onto the light-sensing surface 3A. The funnel is defined by the walls 42A, 42B, which are specularly reflective. It should be noted that the recycler 40 may have other shapes than shown in FIG. 10G. For example, the bottom wall 42A may be parabolic. Other suitable shapes may be obtained by optical system optimization, such as by ray tracing. Furthermore, the walls 42A, 42B may be merged into a common funnel structure, which may be parabolic or have any optimized shape. The recycler 40, and optionally the filter 20, may be integrated with the detector 3 into a package, which is attached to the rear surface 5 during manufacture of the apparatus.

[0104] FIG. 10H illustrates a variant of the outcoupling structure in FIG. 4. In FIG. 10H, the apparatus 100 further comprises a visibility filter 50, which is arranged to hide the angular filter 20, the detector 3 and the internal structure of the apparatus 100 from view through the front surface 5. The visibility filter 50 is non-transmissive (opaque) to visible light and transmissive to NIR light, and preferably only transmissive to NIR light in the wavelength region of the propagating light. The visibility filter 50 may be implemented as a coating or film, in one or more layers. In FIG. 10H, the visibility filter 50 extends from the inner edge of the angular filter 20 to the edge of the panel 1, although the visibility filter 50 may extend further beyond the angular filter 20 towards the center of the panel. In FIG. 10H, the visibility filter 50 is arranged beneath the panel 1, intermediate the rear surface 6 and the angular filter 20. This enables the front surface 5 to be perfectly flat and free of projecting elements. In a variation, not shown, the visibility filter 50 is applied to the front surface 5. It is to be understood that the visibility filter 50 may be implemented in conjunction with any outcoupling structure described herein.

[0105] There are other ways of integrating the angular filter in the outcoupling structure than by arranging the above-described multilayer structure in front of the detector 3. For example, the angular filter may be formed by a structure that geometrically and mechanically limits the light rays that can reach the detector, as exemplified below with reference to FIGS. 11-12.

[0106] FIG. 11A is a side view of a first alternative outcoupling structure as attached to the panel 1, and FIG. 11B is a top plan view of the outcoupling structure. The outcoupling structure forms an angular filter 20 by defining an angularly limited propagation path from an outcoupling port 60 to the light-sensitive surface 3A. The angular filter 20 is defined by non-transmissive layers 61-63 on a body of light transmissive material, e.g. any of the spacer materials discussed in relation to FIG. 10A. Layers 61 and 62 are arranged on top of the body, to define the outcoupling port 60 at the interface between the body and the panel 1. Layer 61 is light-absorbing and formed as an annulus segment. Layer 61 only needs to be absorbing to light inside the body. Layer 62 is specularly reflective and formed as a semi-circle,

which may extend to the inner radius of the annulus segment, as shown, or to the outer radius of the annulus segment (i.e. between layer 61 and the panel 1). The top of the body is attached to the rear surface 5 of the panel 1, and the light detector 3 is attached to a short-side of the body such that the surface 3A is shielded beneath the layers 61, 62. Layer 63 is specularly reflective and attached to bottom side of the body.

[0107] FIG. 11A illustrates one propagating ray P1 that passes the outcoupling port 60 at an AOI within the angular range of the filter 20 and is reflected by layer 63 onto surface 3A. FIG. 11A also illustrates a propagating ray P2 that propagates in the panel 1 by TIR and passes the outcoupling port 60 and is reflected by layer 63 onto layer 61 which absorbs the ray. As seen, the structure of layers 61-63 define the angular range of the filter 20. The width of the layer 61 along the respective detection line defines θ_{min} , for a given vertical height of the body. To achieve similar θ_{min} for all detection lines in the plane of the panel, layer 61 is shaped as an annulus segment, although more complicated shapes are conceivable to achieve a corresponding effect.

[0108] FIG. 12A is a side view of a second alternative outcoupling structure as attached to the panel 1, and FIG. 12B is a top plan view of the outcoupling structure. Like the first variant in FIG. 11, the outcoupling structure forms an angular filter 20 by layers 71-73 attached to a body of light transmissive material which is attached to the rear surface 5 of the panel 1. Layer 71 is arranged on top of the body, to define an outcoupling port 70 at the interface between the body and the panel 1. Layer 71 is specularly reflective and, in this example, formed as a semi-circle. Layer 72 is light-transmissive and attached to the bottom surface of the body, and has a refractive index that causes light that impinges on the outcoupling port 70 at AOIs above θ_{min} to be reflected by TIR at the interface between the body and layer 72, whereas light at smaller AOIs is transmitted into layer 72 and is absorbed by layer 73 of light-absorbing material. It is realized that the refractive index of layer 72 is given by $n_{72} = n_{panel} \sin(\theta_{min})$. The function of the outcoupling structure exemplified by one ray P1 that passes the filter 20 and one ray P2 that is coupled into layer 72.

[0109] In both of the first and second variants, it is conceivable that the refractive index n_{spacer} of the body is selected to yield a desired θ_{max} by TIR in the interface between the body and the panel: $n_{spacer} = n_{panel} \sin(\theta_{max})$.

[0110] Embodiments of structures for incoupling of light will now be explained in detail with reference to FIG. 13. Generally, these embodiments are presented in the context of the touch-sensitive apparatus shown in FIG. 2A.

[0111] FIG. 13A illustrates a section that may be taken along any one of the detection lines D of the touch-sensitive apparatus in FIG. 2A. For the sake of simplicity, only a portion of the apparatus at and around the incoupling structure is shown. The embodiment of FIG. 13A is a rear side coupled solution, in which the incoupling structure comprises a prism 25 configured to direct light from the VCSEL array emitter 2 into the panel 1. More specifically, the prism 25 is preferably configured so as to couple light from the emitter 2 into the panel 1 along a general beam direction having an advantageous angle θ of incidence to the front 5 and rear surfaces 6. Obviously, the angle θ shall be larger than the critical angle θ_c . Preferably, the beam angle θ is such that substantially all light from emitter 2 falls within the angular range $\theta_{min} - \theta_{max}$ of the angular filter 20. Recall that in a panel 1 with a refractive index of 1.5 the

beam divergence of a VCSEL array emitter 2 may be in the region of 12°. The prism 25 may be made from the same material as the panel 1, or any other material which is transmissive to the wavelength of the emitter 2. Dependent on the specific configuration, the prism 25 may also have a reflective surface 27, rather than having a simply refractive function. For the purpose of optimizing the optical coupling, an index-matching component 29 may further be disposed to link the emitter 2 to the prism 25, such as e.g. a layer of silicone.

[0112] FIG. 13B illustrates a bottom plan view of an embodiment of the incoupling structure of FIG. 13A. While it is beneficial that the emitter 2 has a narrow beam divergence vertically, i.e. in the θ direction, it is in some embodiments nevertheless preferable that the divergence ϕ in the horizontal plane is comparatively wide. The reason is that light from one emitter 2 then can be detected by several detectors 3 dispersed along the periphery of the touch surface 4, as seen in FIG. 2A. One way of obtaining this is to sweep the beam from the emitter 2 over the angular range of interest in the plane of the panel 1. Another way is to optically modify the beam shape from the emitter 2, so as to be more fan-shaped. FIG. 13B schematically illustrates one way of obtaining this effect. In this embodiment, the surface 27 of the prism 25 in which the beam from the VCSEL array emitter 2 is reflected, has a microstructure with repeated curved portions, each portion forming a convex mirror from the inside of the prism 25. This way, light from the emitter 2 may be dispersed in the horizontal plane of the panel, as schematically indicated by the dashed arrows. In the drawing of FIG. 13B there is no index-matching component 29 illustrated, but such a component may of course still be employed.

[0113] FIG. 13C illustrates an alternative to the embodiments of FIGS. 13A and 13B. This embodiment makes use of an edge-coupled design, i.e. where light from the emitters 2 is coupled in through a side edge 28 of the panel 1 rather than through the front 5 or rear 6 surface. In the exemplary embodiment of FIG. 13C, a beam direction from the VCSEL array emitter 2 with a suitable angle of incidence to the front 5 and rear 6 surfaces is obtained by means of a wedged shape of the side edge 28, at least at the incoupling site. The VCSEL array emitter 2 may be attached directly to the side edge 28 by means of an index-matching adhesive such as silicone 29. An alternative solution (not shown) may be to couple light from the emitters 2 to the side edge 28 by means of an optical fiber. The embodiment of FIG. 3C is only presented in a side sectional view, but it should be understood that also in this embodiment the incoupling structure at 28 may be configured to spread the emitter light in a fan shape in the panel.

[0114] The incoupling structures of FIGS. 13 A-C are intended to illustrate a few different ways of coupling light into the panel 1 at a suitable angle, but the shown embodiments are not intended to be seen as exclusive examples. Also, it should also be noted that the above-described visibility filter (cf. 50 in FIG. 10H) may be implemented in conjunction with any incoupling structure described herein, e.g. intermediate the panel 1 and the emitter 2, even though the visibility filter has been left out in FIGS. 13A-C.

[0115] FIG. 14 is a bottom plan view of a part of a touch-sensitive apparatus, to illustrate a sequence of emitters 2 and/or detectors 3 that are optically coupled to a panel 1 near one of the panel edges, via a visibility filter 50 which

is applied to the rear surface 6 to extend as a coherent, elongate strip along the panel edge. Each emitter 2 and detector 3 is coupled to the panel 1 by a coupling structure. For the emitters 2 the coupling structure may comprise a prism 25, and for the detectors 3 this coupling structure may comprise an angular filter 20 and a recycler 40. The combination of angular filters 20 and recyclers 40 are arranged as discrete units along the panel edge. It shall be noted that the neither the shape nor the specific location of the respective emitters 2 and detectors 3, and their coupling structures, necessarily reflect an optimum configuration. On the contrary, FIG. 14 is merely intended to provide a schematic representation to indicate the distribution of the emitters 2 and detectors 3 over a common visibility filter 50.

[0116] While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiments, it is to be understood that the invention is not to be limited to the disclosed embodiments, but on the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and the scope of the appended claims.

[0117] The foregoing description indicates that certain selections of the lower limit θ_{min} (e.g. with respect to the cutoff angles $\theta_{c,i}$, θ_w , θ_f) results in significant performance improvement. However, it is possible that performance improves gradually as the lower limit θ_{min} is increased from the critical angle θ_c , e.g. in steps 1°, at least in certain installations. Testing of a certain installation may thus indicate that an acceptable performance improvement is attained at another selected θ_{min} , e.g. any angle between θ_c and θ_w , between θ_w and θ_f and between θ_f and θ_{sc} . The same applies to the selection of refractive index of the lamination layer for suppressing the influence of contamination via the cutoff angle $\theta_{c,i}$.

1. A touch-sensitive apparatus, comprising:

a light transmissive panel comprising a front surface and an opposite, rear surface;

a plurality of light emitters configured to optically connect to the panel and further configured to generate light that propagates by total internal reflection inside the panel across a touch-sensitive region on the panel;

a plurality of light detectors configured to optically connect to the panel and further configured to define a grid of propagation paths across the touch-sensitive region between pairs of light emitters and light detectors;

wherein each of said light emitters comprises a vertical-cavity surface-emitting laser ("VCSEL") array, each said VCSEL array including a plurality of VCSELs configured to be driven in parallel to collectively form one light emitter.

2. The touch-sensitive apparatus of claim 1,

wherein each light detector is optically connected to the light transmissive panel via an angular filter which is applied to an outcoupling region of the light transmis-

sive panel and is configured to transmit the propagating light only within a confined range of angles with respect to the normal of the outcoupling region; and wherein each light emitter is optically connected to an incoupling region of the light transmissive panel and is configured to transmit a beam of light for total internal reflection so as to reach the outcoupling region at least partially within said confined range of angles.

3. The touch-sensitive apparatus of claim 1,

wherein a bandpass filter, tailored to an operating wavelength for said VCSELs, is arranged at said detectors.

4. The touch-sensitive apparatus of claim 3,

wherein said bandpass filter has a bandwidth of less than 5 nm.

5. The touch-sensitive apparatus of claim 2,

wherein the confined range extends from a lower angle limit to an upper angle limit θ_{max} , wherein the lower angle limit θ_{min} is equal to or larger than a critical angle θ_c , which is given by $\theta_c = \arcsin(1/n_{panel})$, with n_{panel} being the refractive index of the light transmissive panel at the outcoupling region.

6. The touch-sensitive apparatus of claim 2,

wherein said outcoupling region is arranged on at least one of the front and rear surfaces.

7. The touch-sensitive apparatus of claim 2,

wherein said incoupling region is arranged on at least one of the front and rear surfaces.

8. The touch-sensitive apparatus of claim 2,

wherein said incoupling region is arranged on a side edge of the panel, connecting the front and rear surfaces.

9. The touch-sensitive apparatus of claim 2, wherein the lower angle limit θ_{min} exceeds the critical angle by an angle $\Delta\theta$, which is at least 5°, 10° or 15°.

10. The touch-sensitive apparatus of claim 2, wherein the lower angle limit θ_{min} is equal to or larger than a first cut-off angle $\theta_w = \arcsin(n_w/n_{panel})$, with n_w being the refractive index of water, $n_{panel} > n_w$.

11. The touch-sensitive apparatus of claim 2, wherein the lower angle limit θ_{min} is equal to or larger than a second cut-off angle $\theta_f = \arcsin(n_f/n_{panel})$, with n_f being the refractive index of finger fat, $n_{panel} > n_f$.

12. The touch-sensitive apparatus of claim 2, wherein the angular filter is configured as a dielectric multilayer structure.

13. The touch-sensitive apparatus of claim 2, wherein the light transmissive panel is mounted onto a front surface of a display device by a lamination layer of light transmissive material which is arranged in contact with the rear surface of the light transmissive panel and the front surface of the display device, and wherein the lower angle limit θ_{min} is equal to or larger than a laminate cut-off angle $\theta_{c1} = \arcsin(n_{lam}/n_{panel})$, with n_{lam} being the refractive index of lamination layer, n_{lam}/n_{panel} .

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