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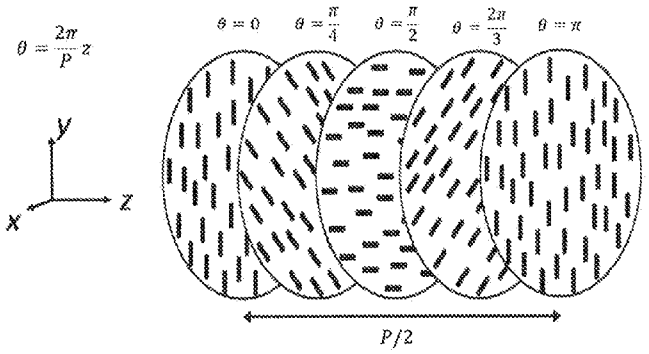
(54) Title: LIQUID CRYSTAL STATE SWITCHING

Figure 9



(57) Abstract: A method of controlling a helicoidal liquid crystal material wherein the liquid crystal material has a negative dielectric anisotropy $\Delta\varepsilon$ satisfying $\Delta\varepsilon = \varepsilon M - \varepsilon\chi < 0$, where εM is the dielectric constant parallel to the helical axis of the liquid crystal material and $\varepsilon\pm$ is the dielectric constant perpendicular to the helical axis of the liquid crystal material, such that in a state without flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field. The liquid crystal material can undergo flexoelectric coupling with an applied electric field as a result of an effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis given by $\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{,,} + \varepsilon_{\perp})/2 > \varepsilon_{\perp}$, where ε_{flexo} is a contribution from flexoelectric polarisation in the material, such that in a state with flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned perpendicular to an applied electric field. The method comprises applying an electric field to the material and changing one or more parameters of the electric field so as to enable or suppress said flexoelectric coupling and thereby switch the material between lowest energy alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

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Liquid Crystal State Switching

The present invention relates to methods of controlling a liquid crystal material and to liquid crystal devices, in particular to switching a liquid crystal material between different alignment states.

Liquid crystal (LC) materials have found wide use in display technologies, which rely on controlling the optical properties of a liquid crystal by applying an electric field. In a typical liquid crystal display (LCD) device, one or more liquid crystal layers are positioned in front of a reflector or backlight to modulate the light passing therethrough. Some conventional displays use a twisted nematic or cholesteric LC between two crossed polarisers so that the polarisation state of light is rotated by 90° after it has passed through the first polariser, allowing it to be transmitted through the second polariser. When an electric field is applied across the LC layer, the molecules tend to align parallel to the electric field due to coupling of the electric field to the dielectric anisotropy of the LC material. This can be visualised in terms of the director reorienting to be parallel with the applied field throughout the LC material. In this state, the LC molecules do not change the polarisation state of light as it passes through, so the device changes transparency with increasing voltage. The applied electric field can be used to make a pixel switch between transparent and opaque (and greyscale in between) on command. The same principle of changing the alignment state of a LC material is used to make various optical devices. As well as displays, liquid crystals can be used to make tuneable optical filters and for optical imaging and recording.

A cholesteric LC phase is a nematic phase that exhibits a spontaneous twist due to chirality of some or all of the molecules of the LC mixture i.e. it has a helicoidal structure with the director rotated slightly between adjacent planes and a helical axis defined normal to the directors. This variation of director is periodic, with the "pitch" of the helicoidal structure being defined as double the period of the angle of the director. Figure 9 illustrates the structure of a helicoidal (e.g. cholesteric) liquid crystal material. The Z-axis defines the helical axis (also known as the helicoidal axis) of the material. It can be seen that the director of the LC molecules is aligned at an angle θ perpendicular to the Z-axis in each layer, and this angle θ varies so that the director rotates with distance along the Z-axis to result in the helicoidal structure. The pitch P is understood to be the distance it takes for the director to rotate one full turn i.e. 2π.

Similar to the mechanism of switching an optical display as described above, the helicoidal structure of a cholesteric LC can be modified by an applied electric field. This can be described in terms of the electric field coupling to the dielectric anisotropy of the liquid crystal. A

material with a positive dielectric anisotropy, i.e. $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} > 0$, naturally adopts a lowest energy state in which the helical axis is aligned perpendicular to the applied electric field. For example, with the material starting in the so-called Grandjean alignment state in which the helical axis (in the bulk) is aligned perpendicular to the bounding surfaces of a liquid crystal device, an electric field can be applied across the surfaces to switch the material into an orthogonal state that has its helical axis aligned parallel to the surfaces, known as a Uniform Lying Helix (ULH) state or conic focal state.

The coupling of the electric field to the dielectric anisotropy of LC materials is the best understood mechanism for controlling the alignment state and optical properties of a liquid crystal. Other methods of controlling the optical properties of a LC material include changes in temperature (e.g. as used in aquarium thermometers) and changes in applied stress or strain (e.g. as used to measure stress distribution patterns). It has also been proposed that some other mechanisms, such as electrohydrodynamic effects or flexoelectric properties, may be harnessed to effect control.

One established method uses electrohydrodynamic effects to help the alignment of a positive dielectric anisotropy material in the ULH state, e.g. as described in: A stable and switchable uniform lying helix structure in cholesteric liquid crystals, Chun-Ta Wang, WeiYuan Wang and Tsung-Hsien Lin, Appl. Phys. Lett. 99 (2011), 041108. The ULH state can switch back to the Grandjean state through a slow relaxation process due to surface interaction with planar alignment layers, which can be enhanced if a large field is applied (unwinding the helix) and the Grandjean state is then allowed to form from the homeotropic state.

In addition to dielectric coupling of the electric field to the dielectric anisotropy of the LC material, an additional flexoelectric effect has been observed in some LC materials, e.g. as described by J. S. Patel and R. B. Meyer in Flexoelectric Electro-optics of a Cholesteric Liquid Crystal, Phys. Rev. Lett. 58, 1538-1540 (1987). In a cholesteric material, a flexoelectric effect can result in a spontaneous polarisation (proportional to splay and/or bend) induced by an electric field that is applied perpendicular to the helical axis. Flexoelectric coupling with the applied electric field tends to keep the molecules in a helical arrangement and can therefore oppose an electric coupling. The effective permittivity, or dielectric constant, may be expressed as $\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{\parallel} + \varepsilon_{\perp})/2$. At frequencies where the flexoelectric contribution ε_{flexo} is present, the critical field that must be applied to unwind the helical ordering may be increased. Patel and Meyer therefore found that the flexoelectric effect can affect how the helicoidal structure of a cholesteric LC is modified or unwound by an applied electric field. This could be used to change when a transition takes place between a helicoidal structure and an unwound (non-helicoidal) structure. However, the mere presence of a flexoelectric effect in this case

does not necessarily allow the material to be switched between alignment states with the helical axis generally aligned perpendicular or parallel to the bounding surfaces of a LC device.

Furtherever, most commercial liquid crystal technology exploits electrical switching within a single state (e.g. switching in the twisted nematic state, switching in the super-twisted nematic state, switching in the vertically aligned state, or in-plane switching in the parallel aligned state) rather than trying to switch between distinct liquid crystal alignment states.

The present invention provides a novel approach to switching between different alignment states of a liquid crystal material.

According to a first aspect of the present invention, there is provided a method of controlling a helicoidal liquid crystal material;

wherein the liquid crystal material has a negative dielectric anisotropy $\Delta\varepsilon$ satisfying:

$$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} < 0 ,$$

where $\varepsilon_{\parallel}$ is the dielectric constant parallel to the helical axis of the liquid crystal material and $\varepsilon_{\perp}$ is the dielectric constant perpendicular to the helical axis of the liquid crystal material, such that in a state without flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field; and

wherein the liquid crystal material can undergo flexoelectric coupling with an applied electric field as a result of an effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis given by:

$$\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 > \varepsilon_{\perp},$$

where ε_{flexo} is a contribution from flexoelectric polarisation in the material, such that in a state with flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned perpendicular to an applied electric field;

the method comprising:

applying an electric field to the material; and

changing one or more parameters of the electric field so as to enable or suppress said flexoelectric coupling and thereby switch the material between lowest energy alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

Thus it will be understood that according to the present invention it is possible to electrically switch a LC material between different alignment states by using an applied electric field to control the presence or suppression of flexoelectric coupling. This is a fundamentally different approach to conventional methods that control the alignment state of a LC material by adjusting the electric field e.g. increasing its amplitude so as to force alignment of the material but without actively harnessing or suppressing a flexoelectric effect. This novel switching mechanism is achieved by using a LC material that has both a negative dielectric anisotropy $\Delta\varepsilon$

and a strong contribution ε_{flexo} from flexoelectric polarisation that is sufficient to change the naturally lowest energy state when the material undergoes flexoelectric coupling. Some examples of a suitable LC material that has a negative dielectric anisotropy and a high flexoelectric response is given below. As a result, the applied electric field can be controlled to switch the helical axis of the LC material between parallel and perpendicular alignment states simply by enabling or suppressing the contribution from the flexoelectric response. In other words, the invention takes advantage of flexoelectric polarisation to controllably modify the material's effective dielectric constant and therefore enable electrical switching between alignment states of the helical axis.

The parameters of the applied electric field that may be adjusted so as to enable or suppress a flexoelectric coupling can be related to changes in amplitude and/or changes in time of an electric field signal. For a time-varying waveform, this may include the amplitude e.g. voltage, the shape of the waveform, the number and/or duration of amplitude pulses, or the pulse sequence applied. For an oscillating waveform, such as an AC electric field, this may include amplitude and/or frequency. The Applicant has recognised that where the applied electric field comprises a time-varying or oscillating signal, the presence of the flexoelectric effect depends on the frequency of the signal. The induced flexoelectric polarisation tends to vary with the applied field. However, there is an associated time constant, dictated mainly by the viscous and elastic properties of the LC material and the pitch of the helicoidal structure. At higher frequencies flexoelectric polarisation is suppressed. The Applicant has realised that this can be harnessed to provide a convenient way of switching the material between alignment states. Thus in a preferred set of embodiments the method comprises changing the frequency of a time-dependent electric field so as to enable or suppress flexoelectric coupling. Changing the frequency can, for example, result in an effective dielectric constant that is largest in a direction perpendicular to the helical axis at low frequencies and largest in a direction parallel to the helical axis at high frequencies.

It will be appreciated that in reality there is no frequency at which there is exactly zero flexoelectric polarization, although it tends toward zero at larger frequencies, and hence the flexoelectric effect is never completely eliminated. However, by changing the frequency (or other parameter), the flexoelectric coupling is reduced to the extent that it is suppressed as compared to the dielectric properties. Then the effective dielectric properties perpendicular and parallel to the helical axis change relative to each other in such a way as to enable switching between orthogonal states with the helical axis either parallel or perpendicular to the applied electric field. It will further be appreciated that one or more other perturbations on the dielectric properties, which is/are not flexoelectric in origin, may possibly be present. However, this would

not change the fact that the present invention is able to switch the LC material between alignment states by using a suppression of the flexoelectric polarisation.

In one set of embodiments the electric field is applied parallel to the initial alignment state of the liquid crystal material, i.e. parallel to the helical axis. In the absence of a flexoelectric effect, the material naturally has a lowest energy alignment state in which the helical axis is aligned parallel to the applied electric field. This means that the step of applying the parallel electric field (e.g. a high frequency AC field) may not change the state of the LC material. The step of changing the electric field parameter(s) (e.g. switching to low frequency) can then be used to enable a flexoelectric coupling and switch the LC material from its initial alignment state to a different alignment state i.e. with its helical axis perpendicular to the applied field. However, if the step of applying the parallel electric field (e.g. a low frequency AC field) enables a flexoelectric coupling then the helical axis tends to align perpendicular to the applied field and the LC material is thereby switched from its initial alignment state to an orthogonal alignment state. The step of changing the electric field parameter(s) (e.g. switching to high frequency) can then be used to suppress the flexoelectric coupling and the LC material is then switched back to its initial alignment state, with its helical axis again parallel to the applied electric field.

In another set of embodiments the electric field is applied perpendicular to the initial alignment state of the liquid crystal material, i.e. perpendicular to the helical axis. In the absence of a flexoelectric effect, the material naturally has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field. Again, this means that the step of applying the perpendicular electric field may have two possible outcomes, depending on whether or not the step of applying the electric field enables a flexoelectric coupling.

In a first sub-set of embodiments, the parameters of the perpendicular electric field (e.g. high frequency) do not allow flexoelectric coupling so that the LC material switches to its natural lowest energy alignment state in which the helical axis is aligned parallel to the applied electric field. The step of applying the perpendicular electric field therefore switches the material from its initial alignment state to an orthogonal alignment state. The step of changing the electric field parameter(s) (e.g. switching to low frequency) can then be used to access a flexoelectric coupling so that the helical axis tends to align perpendicular to the applied field and the LC material is thereby switched back to its initial alignment state. In a second sub-set of embodiments, the parameters of the perpendicular electric field (e.g. low frequency) enable a flexoelectric coupling so that the helical axis tends to remain aligned perpendicular to the applied field. The step of changing the electric field parameter(s) (e.g. switching to high frequency) can then be used to suppress the flexoelectric coupling and the LC material is then

switched from its initial alignment state to a lower energy state with its helical axis aligned parallel to the applied electric field.

It will be appreciated that switching the LC material between alignment states is a reversible and bi-directional process. Accordingly the step of changing one or more parameters of the electric field may comprise changing the parameter(s) one or more times. For example, the frequency of the applied electric field may be increased/decreased to switch the LC material from one alignment state to another, and then subsequently decreased/increased to switch the LC material back between the alignment states. Of course parameter(s) other than frequency may be changed back and forth in a similar manner. This may be repeated e.g. at regular or irregular intervals to provide for repeated switching of the LC material between different alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

So far the invention has been described in the context of a liquid crystal material having constant material properties, which is electrically switched between different alignment states. However the Applicant has further recognised that another mechanism may be used to enable or suppress the flexoelectric effect, in addition to electrical switching or even as an alternative method of control. By changing material properties, such as dielectric properties or the pitch of the helicoidal structure, the flexoelectric response of the cholesteric LC material may be changed so as to adjust the contribution ε_{flexo} from flexoelectric polarisation in the material. In one set of embodiments the method further comprises changing one or more parameters of the liquid crystal material, so as to enable or suppress flexoelectric coupling and thereby switch the helical axis between perpendicular or parallel alignment with an applied electric field.

This is considered novel and inventive in its own right, and thus when viewed from a second aspect the present invention provides a method of controlling a helicoidal liquid crystal material;

wherein the liquid crystal material has a negative dielectric anisotropy $\Delta\varepsilon$ satisfying:

$$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} < 0 ,$$

where $\varepsilon_{\parallel}$ is the dielectric constant parallel to the helical axis of the liquid crystal material and $\varepsilon_{\perp}$ is the dielectric constant perpendicular to the helical axis of the liquid crystal material, such that in a state without flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field; and

wherein the liquid crystal material can undergo flexoelectric coupling with an applied electric field as a result of an effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis given by:

$$\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 > \varepsilon_{\perp},$$

where ε_{flexo} is a contribution from flexoelectric polarisation in the material, such that in a state with flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned perpendicular to an applied electric field;

the method comprising:

applying an electric field to the material; and

changing one or more parameters of the liquid crystal material so as to enable or suppress said flexoelectric coupling and thereby switch the material between lowest energy alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

It will be appreciated that this provides an alternative mechanism for switching on and off the flexoelectric interaction and therefore changing the effective dielectric constant so as to dictate whether the helical axis tends to align with the applied electric field or not. This may be achieved by changing the dielectric and/or flexoelectric response of the material. Changing one or more parameters of the liquid crystal material may comprise changing one or more parameters that relate to the material's flexoelectric response such as the flexoelectric coefficients (e_1 or e_3), or the elastic coefficients e.g. for splay, twist or bend (K_1, K_2 or K_3). Alternatively, or in addition, changing one or more parameters of the liquid crystal material may comprise changing one or more dielectric properties of the material such as the dielectric constants $\varepsilon_{\parallel}$ and/or $\varepsilon_{\perp}$. In another set of embodiments (again, alternatively or in addition), changing one or more parameters of the liquid crystal material may comprise changing the pitch of the helicoidal structure. For example, the pitch could be varied using optical addressing of photosensitive chiral dopants, or with temperature, or by another means. In embodiments where changing the frequency is used to switch between alignment states, the pitch may also be varied so as to affect the relaxation frequency according to the equation $f_{flexo} = \pi(K_1+K_3)/\gamma P^2$, where K_1 and K_3 are the splay and bend elastic coefficients, γ is a viscosity and P is pitch. In other embodiments the chirality of the material could be changed.

In a further set of embodiments, a molecular structure or configuration of the liquid crystal molecules could be changed. For example, a light-induced trans-cis change in molecular configuration could be used to change the flexoelectric properties, or helicoidal pitch, or another material property, of the liquid crystal material such that switching takes place. For instance light, for example sunlight, could be used to induce a change in material properties that results in switching.

In a further set of embodiments, the liquid crystal material may include dichroic absorbing dyes. This may allow switchable polarising elements to be engineered based on the switching mechanism of changing one or more material parameter(s).

In yet another set of embodiments (again, alternatively or in addition), changing one or more parameters of the liquid crystal material may comprise adding additional species and/or particles to the liquid crystal material to adjust its dielectric properties. It may be possible to incorporate particles in the liquid crystal material (such as, but not limited to, nano-particles, nano-tubes, metallic nano-beads, etc.) in order to modify the material's properties and influence the flexoelectric coupling in order to achieve switching in novel ways. For example, the inclusion of "bent" nano-tubes could potentially enhance the flexoelectric polarisation e.g. at lower frequencies of the applied field, but this effect may not be present e.g. at higher frequencies. This effect is not limited to these particular particles, but may be achieved through the inclusion of a number of types of particles and other molecular species and possibly mixtures of particles and/or molecules with the liquid crystal material.

In a further set of embodiments the incorporation of certain particles or other species in the liquid crystal material could be used to cancel the flexoelectric polarisation e.g. at lower frequencies. Then the lower frequencies would show the smaller flexoelectric polarisation and hence smaller dielectric constant perpendicular to the helicoidal axis, while the higher frequencies would show the larger flexoelectric polarisation and hence larger dielectric constant perpendicular to the helical axis. This could be used to invert the switching scheme. Of course the step of changing material parameter(s) to effect switching may be used alone, or in combination with electrical switching as described above in relation to the first aspect of the invention.

As is described above, the step of applying the electric field may enable a flexoelectric coupling or not. For example, if a high frequency electric field is applied then the material may naturally have a lowest energy alignment state in which the helical axis is aligned parallel to the applied electric field. On the other hand, if a low frequency electric field is applied then a flexoelectric coupling may be enabled that causes the helical axis to align perpendicular to the applied field. As before, the step of applying the electric field may include selecting the parameter(s) e.g. frequency of the electric field so that the material is switched from its initial alignment state to a different, lower energy state in which the helical axis is aligned either perpendicular or parallel to the applied electric field. The parameter(s) of the applied electric field may alternatively be selected so that the material remains in its initial alignment state until one or more parameters of the liquid crystal material are changed so as to switch the alignment of the helical axis in the LC material from one alignment state to another alignment state, or vice versa.

As is mentioned above, it is an advantage of the present invention that a liquid crystal material can be switched between different alignment states by changing its effective dielectric constant, and hence the way it couples with an applied electric field, without necessarily changing the amplitude of the electric field. However, in at least one set of embodiments according to either aspect of the invention, the method may further comprise changing the amplitude of the applied electric field. This could be used, for example, to provide additional switching steps at different times.

When applied to a device, the step of changing one or more parameters of the electric field, or changing one or more parameters of the liquid crystal material, may switch the LC material between a Grandjean state and a Uniform Lying Helix (ULH) or focal conic state, or vice versa. Of course there may be other states which can be accessed, for example Helfrich states or states in other liquid crystal geometries. The switching mechanism applies to any states which can be accessed by enabling or disabling the flexoelectric coupling.

By changing electrical or material parameters to enable or suppress the flexoelectric effect, the effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis of the material can be made larger than the perpendicular component $\varepsilon_{\perp}$, whereas if the flexoelectric polarisation is suppressed the material has $\varepsilon_{effective} = (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 > \varepsilon_{\parallel}$ perpendicular to the helix axis. This switches the material between alignment states in which the helical axis is perpendicular or parallel to an applied electric field. In a liquid crystal device, switching the material between alignment states can change its optical and/or electrical properties.

According to a further aspect of the present invention there is provided a liquid crystal device comprising at least one layer of a helicoidal liquid crystal material between surface plates, wherein the liquid crystal material has a negative dielectric anisotropy $\Delta\varepsilon$ satisfying:

$$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} < 0 ,$$

where $\varepsilon_{\parallel}$ is the dielectric constant parallel to the helical axis of the liquid crystal material and $\varepsilon_{\perp}$ is the dielectric constant perpendicular to the helical axis of the liquid crystal material, such that a state without flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field;
and wherein the liquid crystal material can undergo flexoelectric coupling with an applied electric field as a result of an effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis given by:

$$\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 > \varepsilon_{\perp},$$

where ε_{flexo} is a contribution from flexoelectric polarisation in the material, such that in a state with flexoelectric coupling the material can have a lowest energy alignment state in which the helical axis is aligned perpendicular to an applied electric field;

wherein, in a first device state, an electric field is applied to the material to provide a first alignment state in which the helical axis is aligned in an initial direction that is either parallel or perpendicular relative to the surface plates; and

wherein, in a second device state, one or more parameters of the applied electric field, or one or more parameters of the liquid crystal material, are changed so as to enable or suppress said flexoelectric coupling and thereby switch the material to a second, different, alignment state in which the helical axis is aligned orthogonal to the initial direction relative to the surface plates.

In one set of embodiments the electric field is applied parallel to the surface plates (i.e. in-plane). If flexoelectric coupling is enabled then, in the first device state, the helical axis is aligned perpendicular to the applied electric field in the material's first alignment state. Accordingly the first alignment state may be the Grandjean state in which the helical axis is oriented perpendicular to the surface plates (in the bulk of the liquid crystal material). When the device is switched to the second state so as to suppress the flexoelectric coupling, the liquid crystal material will change to a lower energy state in which its helical axis is aligned parallel to the applied electric field. Accordingly the second alignment state may be the Uniform Lying Helix (ULH) or focal conic state with the helical axis oriented parallel to the surface plates (in the bulk of the liquid crystal material). Alternatively, the first and second alignment states may be swapped if the applied electric field does suppress flexoelectric coupling in the first device state (e.g. a high frequency electric field).

In another set of embodiments the electric field is applied perpendicular to the surface plates (i.e. out-of-plane). If flexoelectric coupling is enabled then, in the first device state, the helical axis is aligned perpendicular to the applied electric field in the material's first alignment state. Accordingly the first alignment state may be the Uniform Lying Helix (ULH) or focal conic state with the helical axis oriented parallel to the surface plates (in the bulk of the liquid crystal material). When the device is switched to the second state so as to suppress the flexoelectric coupling, the liquid crystal material will change to a lower energy state in which its helical axis is aligned parallel to the applied electric field. Accordingly the second alignment state may be the Grandjean state in which the helical axis is oriented perpendicular to the surface plates (in the bulk of the liquid crystal material). Alternatively, the first and second alignment states may be swapped if the applied electric field does suppress flexoelectric coupling in the first device state (e.g. a high frequency electric field).

It will be understood from the discussion above that, when the electric field is applied to create the first device state, this may also change the alignment state of the liquid crystal material. In one set of embodiments the material may be in an initial alignment state, in the absence of an applied electric field, in which the helical axis is oriented perpendicular to the surface plates i.e. the so-called Grandjean state. This may be achieved, for example, by interaction with the surface plates. Applying an electric field to the device may then switch the material from this initial alignment state to a first alignment state that is the focal conic or ULH state. By changing one or more parameters of the applied electric field, or one or more parameters of the liquid crystal material, thereby changing the flexoelectric coupling with the applied field, the material can then be switched to a second alignment state that is back to the Grandjean state. A complete cycle of device states may therefore be achieved. Of course, the device could also be driven in reverse.

In another set of embodiments the material may be in an initial alignment state, in the absence of an applied electric field, in which the helical axis is oriented parallel to the surface plates i.e. the so-called Uniform Lying Helix (ULH) or focal conic state. This may be achieved, for example, by interaction with the surface plates. Applying an electric field to the device may then switch the material from this initial alignment state to a first alignment state that is the Grandjean state. Changing one or more parameters of the applied electric field, or one or more parameters of the liquid crystal material, may then switch the material to a second alignment state that is back to the ULH or focal conic state. A complete cycle of device states may therefore be achieved. Of course, the device could also be driven in reverse.

The liquid crystal device may be any device that can take advantage of controlled switching between alignment states of the LC material in which the helical axis is perpendicular or parallel to an applied electric field. In one set of embodiments the device may be an optical device, for example an optical display device. By selecting the pitch of the helicoidal structure, the Grandjean geometry has been proposed for ultra-fast transmissive displays, and has also been commercialised as a reflective technology. The focal conic texture can be weakly scattering, and has been suggested for use in reflective display technology, including bistable modes. The ULH has long been developed for use as a transmissive display technology, having major advantages over existing technology, including sub-millisecond switching times and the possibility of having an in-plane rotation of the optic axis without the need for complicated interdigitated electrode structures. One potential application is in creating a dual-mode display, which can be switched from a transmissive display (exploiting the ULH switching), to a reflective bi-stable display (exploiting Grandjean and focal conic or ULH textures) by addressing at different frequencies.

A further potential application is in creating a reflective cholesteric display technology, which can be switched from a reflecting state to a non-reflecting state by addressing at different frequencies. Thus in a set of embodiments the liquid crystal device is a reflective display device. Such a bi-stable device can enable the selection of focal conic or Grandjean states using appropriate driving frequencies. When used in front of a dark light-absorbing material, the focal conic state provides a dark, non-reflective state. The cross-over frequency may be adjusted dependent on the pitch of the material. The pitch can be chosen such that the material reflects light of wavelengths λ commensurate with the pitch P of a cholesteric material with average refractive index n, by the relation $\lambda = nP$, thereby producing a bright, reflective state. These devices may allow a much greater flexibility, in comparison with dual-frequency materials, in the choice of other parameters, including surface alignment condition, driving scheme and material parameters. Unlike specially engineered dual-frequency materials, it can be possible to switch between states at frequencies as low as 200 Hz rather than 30 kHz as typically required. Furthermore the LC material may not require polymer network stabilisation.

In a further set of embodiments the device may comprise a switchable diffractive structure. For example, the helicoidal pitch of the material may be appropriately chosen so that one of the alignment states e.g. the ULH state acts as a period structure leading to diffraction, whereas the other alignment state e.g. the Grandjean state does not result in diffraction. The device may then be switched between these two alignment states in order to switch between a diffractive and non-diffractive effect. There may be other related switchable diffractive embodiments.

In a further set of embodiments the device may include one or more emissive material(s) and take advantage of the switching mechanism to influence the resulting emissive properties. For example, the device can form a liquid crystal based lasing system if appropriate emissive materials are included. Switching between the ULH and Grandjean states may then allow switching between edge-emitting and surface-emitting laser systems. There may be many other switchable emissive systems in which the device could be employed.

In a further set of embodiments the device is provided as part of a lens or other optical element. Switching between device states could be exploited in order to engineer novel optical elements. In a further set of embodiments it may be possible to use the switchable device within integrated optics systems. For example, the possibility of switching between alignment states could be used to engineer a switchable Bragg-type reflector in an integrated optical system (such as, but not necessarily limited to, a wave guide) in order to allow switchable wavelength selection etc. There may be many other possible applications within integrated optics systems.

In a further set of embodiments the device could be used as the basis of switchable polarisation filters and related optical elements. For example, by appropriate choice of the material's helicoidal pitch, the Grandjean state could be arranged to act as a circular polariser (through selective reflection). Switching from this alignment state to a ULH state would allow switching of the circular polariser. In a related embodiment, combining the switchable device together with appropriate optical wave plates may allow a switchable linear polariser to be engineered.

In a further set of embodiments the liquid crystal material may comprise a polymer dispersed system, in which switching between alignment states alters the refractive index mismatch to control scattering, for example, or to produce another optical effect. Liquid crystal materials that are immiscible or otherwise prevented from mixing, e.g. through a polymer dispersed system, could have a different helical pitch, chirality or other properties. This could be exploited in a single device for increased functionality, e.g. selection of reflected colour(s) or to produce greater reflectivity.

In another set of embodiments, one or more parameters of the liquid crystal material may be altered through the absorption of external particles or chemical entities that may be present in the ambient environment e.g. surrounding a liquid crystal device. Such a device could therefore find use as a detector.

Of course the liquid crystal device may comprise more than one layer of a cholesteric liquid crystal material, or multiple layers comprising a cholesteric liquid crystal material layer together with one or more layers of a non-cholesteric liquid crystal material. The multiple layers could be addressed by the same electric field, e.g. in order to achieve a brighter reflectance or additional functionality, such as wavelength or reflective selectivity. For example, a three-layer device maybe addressed by changing the driving frequency of an applied electric field in order to switch the layers independently to select a desired reflectivity spectrum or colour(s). The multi-layer device could also be addressed by using multiple electrode arrangements, e.g. by different electrodes for each layer.

The liquid crystal device may comprise one or more polarisers, compensating filters, transmission windows, or the like, as desirable to take advantage of the switching between alignment states e.g. to produce a controllable display. The LC device may take the form of a window that reflects a particular frequency of electromagnetic radiation, e.g. infrared or ultraviolet light, but whose reflectivity at these wavelengths can be controlled by switching between alignment states.

Where reference is made to a particular alignment state, it will be understood that what is meant is that the helical axis in the bulk of the LC material is generally aligned parallel or perpendicular to an applied electric field or to the bounding surfaces of a device. There may be a variety of near-surface transition regions present e.g. depending on the details of the surface

alignment used. The Grandjean state, also known as the Uniform Standing Helix (USH) state, is one in which the helical axis in the bulk is aligned perpendicular to the bounding surfaces of a liquid crystal device. This state has a range of interesting optical properties depending on whether the helix pitch is substantially less than the wavelength of light, similar to the wavelength of light, or substantially greater than the wavelength of light. Another distinct alignment state is one in which the helical axis in the bulk is aligned generally parallel with the bounding surfaces of a liquid crystal device (again there may be a variety of surface transition regions present depending of the nature of the surface alignment used). This state has a number of sub-forms, but two key ones mentioned above are where the helical axis has no preferential direction, leading to what is commonly called the focal conic state, and one where there is a well-defined orientation of the axis in the bulk, leading to what is commonly called the Uniform Lying Helix (ULH) state. However the focal conic state or ULH state may be interchanged with any other alignment state in which the helical axis in the bulk is aligned generally parallel, including mixtures of these two states or intermediary states.

A liquid crystal (LC) material is one existing in a liquid crystalline phase, usually defined as having a significant anisotropic orientational structure and short-range orientational order while still having an ability to flow. A large number of chemical compounds have been identified as having a liquid crystalline phase. The cholesteric liquid crystal material may comprise one or more different liquid crystal materials, for example a mixture of liquid crystal materials. To be classed as a cholesteric material (also known as twisted nematic or chiral nematic) the liquid crystal structure must have an overall lack of axial symmetry due to chirality i.e. a helicoidal structure. In such materials the helicity may be obtained through the use of chiral materials, or chiral doping, or by other means such as the use of a polymer network, or by any other means. The LC material may comprise one or more nematic materials, that are either chiral or achiral. The overall dielectric anisotropy $\Delta\varepsilon$ of the material can be measured e.g. from capacitance data according to standard techniques. Measuring the capacitance C provides the effective dielectric properties, i.e. $C = \varepsilon_\chi \varepsilon_0 A/d$, where A is the area of the capacitor and d is the separation in the plates of the capacitor. The LC permittivity can therefore be measured by measuring the cell capacitance and comparing it to the empty cell capacitance to eliminate A and d.

The other requirement of the LC material is that it provides a flexoelectric contribution ε_{flexo} to the dielectric properties which is sufficient to change which alignment state is the lowest energy state. In practice this may result from a high flexoelectric coefficient $e_1 - e_3$ and/or, in some situations, a high flexoelectric coefficient $e_1 + e_3$. A standard method for determining the flexoelectric coefficient ε_{flexo} involves measuring the rotation in the optic axis of a material in the ULH geometry to determine $e_1 - e_3$ using the relation $\theta = (e_1-e_3)PE/(K_1+K_3)2\pi$, where θ is optic

axis rotation, P is pitch, E is electric field, and K_1 and K_3 are the splay and bend elastic coefficients. See, for example, Flexoelectric coefficient measurements in the nematic liquid crystal phase of 5CB, F. Castles *et al.*, AIP Advances, Vol. 2, 022137 (2012). Another standard method for determining the flexoelectric coefficient ε_{flexo} arising from $e_1 + e_3$ is the Hybrid Aligned Nematic (HAN) method e.g. as described in Flexoelectricity in the Hybrid Aligned Nematic Cell, B. Valenti *et al.*, Molecular Crystals and Liquid Crystals, Vol. 146, pp. 307-320 (1987).

Many different LC materials may be found, or tailored, to have a negative dielectric anisotropy and the necessary flexoelectric response. The skilled person will be able to select a suitable LC material by measuring its dielectric anisotropy and flexoelectric response.

Example 1

An exemplary material having suitable properties is a liquid crystal mixture A comprising 60% by weight MDA-1245 and 40% by weight MLC-7029 (both obtained from Merck). MDA-1245 is a highly chiral LC material. MLC-7029 is an achiral nematic LC material having a negative dielectric anisotropy $\Delta\varepsilon$ of -3.7. As the flexoelectric response of MLC-7029 is small, it is mixed with MDA-1245, a bimesogen mixture having a high flexoelectric coefficient $e_1 - e_3$ and a small dielectric anisotropy $\Delta\varepsilon$. The presence of MLC-7029 gives the material an overall negative dielectric anisotropy $\Delta\varepsilon$ while MDA-1245 provides a flexoelectric contribution ε_{flexo} to the dielectric properties that is sufficient to change which orientation of the helicoidal axis corresponds to the lowest energy state when the field frequency (or another parameter) is altered to enable or suppress the flexoelectric interaction. The overall dielectric anisotropy of mixture A was determined from capacitance data to be -0.5 at 40 °C.

To prepare a suitable device, the liquid crystal mixture A was capillary filled while in the isotropic phase into a cell comprising two glass substrates with anti-parallel aligned polyimide alignment surfaces. The cell gap between glass substrates is of thickness 5μm, and there is indium-tin-oxide on both substrate surfaces in order to apply a transverse field to the liquid crystal. A 2 kHz electric field of 20 V_{rms} was applied transverse to the liquid crystal film. The initial alignment state of the device, shown in Figure 1a, is a Grandjean texture. If the electric field is removed and the device is left (e.g. for 30 s) then the Grandjean texture is seen to remain, showing that this initial alignment state is stable over long periods. From the Grandjean state there are two other alignment states that are easily accessible.

Starting from the Grandjean texture, if a 100 Hz electric field of amplitude 4 $V\mu m^{-1}$ is applied to the cell then the LC material is seen to spontaneously form a Uniform Lying Helix (ULH) alignment state, shown in Figure 1b, if left with this driving regime for several seconds. The applied electric field signal is thought to align the ULH state by a combination of interaction

with the alignment layer and electrohydrodynamic effect. On removal of the electric field, the ULH state is stable for several minutes before slowly beginning to revert to a Grandjean texture.

Starting from the Grandjean texture, if an electric field of frequency 300 Hz is applied instead, then the cell will form the focal conic texture rather than the ULH state, as is shown by Figure 1c. This may be because at this frequency electrohydrodynamic effects are suppressed, which appear to be important in aligning the ULH in a direction determined by the surface anti-parallel alignment conditions.

From either the ULH or focal conic state, the cell can be driven in approximately 100 ms back to the Grandjean state by changing the frequency of the applied electric field from 100 Hz or 300 Hz to 2 kHz. Figure 1d shows the Grandjean texture accessed in the same cell by the application of a 2 kHz driving field. The series of optical micrographs in Figures 1a to 1d therefore illustrates a complete cycle of state switching from Grandjean to ULH or focal conic and back again to Grandjean, by using appropriate driving frequencies at each stage.

Figure 2 shows the capacitance of the cell as a function of frequency whilst in the Grandjean i.e. Uniform Standing Helix (USH) state, the Uniform Lying Helix (ULH) state, and the focal conic state. The Grandjean capacitance is roughly independent of frequency, until frequencies higher than 1000 Hz. On the other hand, the ULH and focal conic states exhibit a larger capacitance (and therefore dielectric magnitude) at 100 Hz and a smaller capacitance at larger frequencies compared to the Grandjean state. There is a cross-over point at approximately 660 Hz. This capacitance data illustrates the reason the device can switch between two different alignment states depending on frequency. At low frequencies, the ULH and focal conic states are of lower energy than the Grandjean state, and the reverse is true at high frequencies. The change in dielectric properties and capacitance of the ULH and focal conic states is due to the time constant associated with the flexoelectric polarisation, which is dependent upon the pitch and viscous and elastic properties of the liquid crystal material. The time constant controlling the frequency at which the dielectric constant drops corresponds well to the electro-optic measurements of the flexoelectric switching.

Figure 3 shows the measured capacitance of the 5μm cell as a function of frequency for both the ULH and Grandjean states, together with the appropriate fits to the data from analytical relaxation models. The amplitude of the signal used for the capacitance measurement is 100 mV, which is not large enough to switch the state of the cell. Fitting the ULH capacitance data to an analytical model for the dielectric constant of a liquid crystal material provides the following values for a cell area of 1 cm^2:

$\varepsilon_{flexo} = 0.87$

$\varepsilon_{\infty} = (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 = 7.7$

$\varepsilon_{\perp} = 7.9.$

The capacitance data show that for material A, there is a relaxation in the dielectric properties of the material when in the ULH geometry, such that the permittivity crosses over that of the Grandjean geometry at a frequency of approximately 700 Hz. Using the relaxation model, we find the characteristic time of the relaxation
is 350 μs, corresponding to 448 Hz. This is supported by electro-optic measurements of switching in the ULH geometry, shown in Figure 4, which further support that the relaxation is due to flexoelectricity. Figure 4 shows the voltage signal (before amplification by 10X for application to the cell) in the top plot, and the optical response of the device whilst in the ULH state in the bottom plot. The electro-optic response was taken using a photodiode attached to an optical polarising microscope. The polariser and analyser are set at 90°, and white light is incident on the device. The optic axis of the ULH state when there is no field applied is at 22.5° to the polariser axis. The response is typical of flexoelectrooptic switching in the ULH state, and shows a characteristic switching time (the time for the transmission to reach within 1/e of the new value after a field polarity inversion) of approximately 333 μs (NB. this is not the rise time shown in Fig. 4, which does not represent the 1/e time). The midpoint of the change in dielectric constant and capacitance occurs when $\omega_\tau=1$. For a 1/e time of 333 μs this corresponds to a frequency of 478 Hz, which is within 7% of the observation of 448 Hz from the model fit to the data shown in Figure 3, and this is a good agreement considering the error in the measurement of the time constant. In combination with the overall quality of the theoretical fit in Figure 3, this result provides strong evidence that the change in dielectric properties with frequency causing the cross-over in dielectric properties of different states, as observed in Figure 2, is indeed due to the contribution to the dielectric properties of the material due to flexoelectricity.

The capacitance data and electro-optic measurements have shown that there is a relaxation in the relative permittivity of material A, that this relaxation is due to the suppression in the flexoelectric switching at high frequencies, and that this allows a change in the lowest energy state of the liquid crystal material at a cross-over frequency. The device can therefore switch between ULH and Grandjean states simply by changing the frequency of the applied electric field.

Example 2

A liquid crystal mixture B comprises 40% by weight of MLC-7029 (obtained from Merck) and 60% by weight of MDA-10-4409 (obtained from Merck). MLC-7029 is a nematic having negative dielectric anisotropy at room temperature, while MDA-10-4409 is a high flexoelectricity, bimesogenic liquid crystal. Mixture B was doped with small amounts of high-twisting-power chiral additive R5011, in order to obtain a range of desired pitch lengths. Two samples of mixture B were filled into planar-aligned cells and allowed to form the Grandjean texture. The

two samples had Bragg reflection maxima, as measured on a spectrometer, centred on 480 and 590 nm. The samples were then capillary-filled in the isotropic phase into 5 micron thick cells that had been produced with top and bottom electrodes order to apply an electric field, and a homeotropic surface alignment condition. This is in contrast to most reflective cholesteric devices, which commonly use planar surface alignment conditions to allow the planar Grandjean state to be accessed via an elastic interaction with the surface. Here, however, because we do not rely on this mechanism for switching, we have chosen to demonstrate the technology with homeotropic anchoring, which greatly increases the viewing angle without the need for a polymer network.

On application of a 5 kHz, 10 V_{rms} μm^{-1} signal, the device is driven into the Grandjean texture, which is stable for long periods once the field is removed.
On application of 100 Hz, 10 V_{rms} μm^{-1}, the devices are driven into the focal conic state, which is also stable for long periods. The Bragg behaviour in the Grandjean state and scattering efficiency in the focal conic state is illustrated by transmission spectra of the devices, shown in Figure 5. The two samples show dips in transmission consistent with a Bragg reflection when the material has a Grandjean texture under the application of 5 kHz. The Bragg behaviour is completely absent once the cells are driven into the focal conic state, where they have almost identical transmission characteristics, consistent with a weakly scattering focal conic state. The states are confirmed with polarizing microscopy.

The cross-over in the dielectric properties of the two stable states due to suppression of the flexoelectric polarisation is seen from the capacitance measurements shown in Figure 6. Capacitance is plotted as a function of frequency (using the 100 mV test voltage) for cells filled with the two samples of mixture B while in stable focal conic and Grandjean states. At frequencies below the cross-over frequency, for a given sample, the focal conic state has a larger capacitance than the Grandjean state. At frequencies beyond the relaxation, the focal conic capacitance is lower than the Grandjean. A larger capacitance implies a larger effective dielectric permittivity, and the larger component of the permittivity will have a tendency to re-orient parallel to the applied field, in order to minimise the electric potential energy. While the cross-over frequency is pitch dependent, the ability to switch between states is not affected by pitch variation. It can be seen that the cross-over frequency for material B is between 200 and 400 Hz, orders of magnitude smaller than the ε_{II} relaxation frequency in specially engineered dual-frequency materials previously used in this context.

It may be possible to reduce the flexoelectric bimesogenic component of the mixture in order to provide a greater negative dielectric anisotropy without compromising dual-frequency switching functionality. The switching time may be affected by the bimesogenic component,

which in mixture B had a very large viscosity. Switching times may be improved by techniques such as the use of polymer networks or the exploitation of Helfrich instabilities.

Comparative Example 1

A liquid crystal material was prepared comprising a mixture of 60% by weight MDA-1245 and 40% by weight BL-087 (obtained from Merck), which is an achiral nematic LC material with a positive dielectric anisotropy. Figure 7 shows the measured capacitance of the cell as a function of frequency. Although the contribution of MDA-1245 is a large flexoelectric contribution at low frequencies in the Uniform Lying Helix (ULH) state, as observed for material A, the positive dielectric anisotropy of BL-087 means that the Grandjean state always has a lower capacitance than the ULH state. Without an overall negative value for the dielectric anisotropy, there is no possibility of switching between alignment states because there is no change in which state has the lowest energy.

Comparative Example 2

A liquid crystal material was prepared comprising MLC-7029 ($\Delta\varepsilon$ of -3.7) mixed with 2.1% by weight of R-5011 (obtained from Merck), a chiral additive. The resulting LC material is cholesteric with an overall negative dielectric anisotropy. Figure 8 shows the measured capacitance of the cell as a function of frequency. This material does not provide a sufficient contribution ε_{flexo} from flexoelectric polarisation in the material to be able to lift the capacitance of the ULH state higher than the Grandjean state at low frequencies. Hence there is no possibility of switching between the alignment states of this material by changing the frequency of the applied electric field.

Claims

1. A method of controlling a helicoidal liquid crystal material;

wherein the liquid crystal material has a negative dielectric anisotropy $\Delta\varepsilon$ satisfying:

$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} < 0$,

where $\varepsilon_{\parallel}$ is the dielectric constant parallel to the helical axis of the liquid crystal material and $\varepsilon_{\perp}$ is the dielectric constant perpendicular to the helical axis of the liquid crystal material, such that in a state without flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field; and

wherein the liquid crystal material can undergo flexoelectric coupling with an applied electric field as a result of an effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis given by:

$\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 > \varepsilon_{\perp}$,

where ε_{flexo} is a contribution from flexoelectric polarisation in the material, such that in a state with flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned perpendicular to an applied electric field;

the method comprising:

applying an electric field to the material; and

changing one or more parameters of the electric field so as to enable or suppress said flexoelectric coupling and thereby switch the material between lowest energy alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

2. A method according to claim 1, comprising selecting the parameters of the electric field so that the step of applying the electric field enables said flexoelectric coupling.

3. A method according to claim 1, comprising selecting the parameters of the electric field so that the step of applying the electric field suppresss said flexoelectric coupling.

4. A method according to claim 1, 2 or 3, comprising selecting a parameter of the electric field so that the step of applying the electric field switches the material between alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

5. A method according to any preceding claim, wherein the step of changing one or more parameters of the electric field comprises changing the parameter(s) one or more times.

6. A method according to any preceding claim, wherein the step of applying an electric field comprises applying a time-varying electric field and the step of changing one or more parameters of the electric field comprises changing the frequency of the electric field so as to enable or suppress flexoelectric coupling.

7. A method according to any preceding claim, further comprising changing one or more parameters of the liquid crystal material, so as to create or remove flexoelectric coupling, and thereby switch the material to a different, lower energy state that is aligned either perpendicular or parallel to the applied electric field.

8. A method of controlling a helicoidal liquid crystal material;

wherein the liquid crystal material has a negative dielectric anisotropy $\Delta\varepsilon$ satisfying:

$$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} < 0 ,$$

where $\varepsilon_{\parallel}$ is the dielectric constant parallel to the helical axis of the liquid crystal material and $\varepsilon_{\perp}$ is the dielectric constant perpendicular to the helical axis of the liquid crystal material, such that in a state without flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field; and

wherein the liquid crystal material can undergo flexoelectric coupling with an applied electric field as a result of an effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis given by:

$$\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 > \varepsilon_{\perp},$$

where ε_{flexo} is a contribution from flexoelectric polarisation in the material, such that in a state with flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned perpendicular to an applied electric field;

the method comprising:

applying an electric field to the material; and

changing one or more parameters of the liquid crystal material so as to enable or suppress said flexoelectric coupling and thereby switch the material between lowest energy alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

9. A method according to claim 8, wherein changing one or more parameters of the liquid crystal material comprises changing the dielectric and/or flexoelectric response of the material.

10. A method according to claim 8 or 9, wherein changing one or more parameters of the liquid crystal material comprises changing a parameter chosen from one or more of: (i) a flexoelectric coefficient; (ii) an elastic coefficient; (iii) a dielectric constant; (iv) a pitch of the liquid crystal material; (v) a molecular structure or configuration of the liquid crystal molecules; or (vi) chirality.

11. A method according to claim 8, 9 or 10, wherein changing one or more parameters of the liquid crystal material comprises adding one or more particles or liquid crystal species to the material.

12. A method according to any of claims 8-11, comprising selecting the parameters of the electric field so that the step of applying the electric field enables said flexoelectric coupling.

13. A method according to any of claims 8-11, comprising selecting the parameters of the electric field so that the step of applying the electric field suppresses said flexoelectric coupling.

14. A method according to any of claims 8-13, comprising selecting the electric field so that the step of applying the electric field switches the material between alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

15. A method according to any of claims 8-13, comprising selecting the electric field so that the step of applying the electric field does not switch the material between alignment states.

16. A method according to any of claims 8-15, further comprising changing one or more parameters of the electric field so as to enable or suppress flexoelectric coupling, and thereby switching the material between alignment states in which the helical axis is aligned either perpendicular or parallel to the applied electric field.

17. A method according to any preceding claim, wherein changing one or more parameters of the electric field, or changing one or more parameters of the liquid crystal material, switches the material between two or more of: (a) a Grandjean state; and (b) a Uniform Lying Helix (ULH) or focal conic state; and (c) any other states which can be accessed by enabling or suppressing said flexoelectric coupling.

18. A liquid crystal device comprising at least one layer of a helicoidal liquid crystal material between surface plates, wherein the liquid crystal material has a negative dielectric anisotropy $\Delta\varepsilon$ satisfying:

$$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} < 0 ,$$

where $\varepsilon_{\parallel}$ is the dielectric constant parallel to the helical axis of the liquid crystal material and $\varepsilon_{\perp}$ is the dielectric constant perpendicular to the helical axis of the liquid crystal material, such that a state without flexoelectric coupling the material has a lowest energy alignment state in which the helical axis is aligned parallel to an applied electric field;
and wherein the liquid crystal material can undergo flexoelectric coupling with an applied electric field as a result of an effective dielectric constant $\varepsilon_{effective}$ perpendicular to the helical axis given by:

$$\varepsilon_{effective} = \varepsilon_{flexo} + (\varepsilon_{\parallel} + \varepsilon_{\perp})/2 > \varepsilon_{\perp},$$

where ε_{flexo} is a contribution from flexoelectric polarisation in the material, such that in a state with flexoelectric coupling the material can have a lowest energy alignment state in which the helical axis is aligned perpendicular to an applied electric field;

wherein, in a first device state, an electric field is applied to the material to provide a first alignment state in which the helical axis is aligned in an initial direction that is either parallel or perpendicular relative to the surface plates; and

wherein, in a second device state, one or more parameters of the applied electric field, or one or more parameters of the liquid crystal material, are changed so as to enable or suppress said flexoelectric coupling and thereby switch the material to a second, different, alignment state in which the helical axis is aligned orthogonal to the initial direction relative to the surface plates.

19. A device according to claim 18, wherein the first device state comprises a Grandjean state and the second device state comprises a Uniform Lying Helix (ULH) or focal conic state.

20. A device according to claim 18, wherein the first device state comprises a Uniform Lying Helix (ULH) or focal conic state and the second device state comprises a Grandjean state.

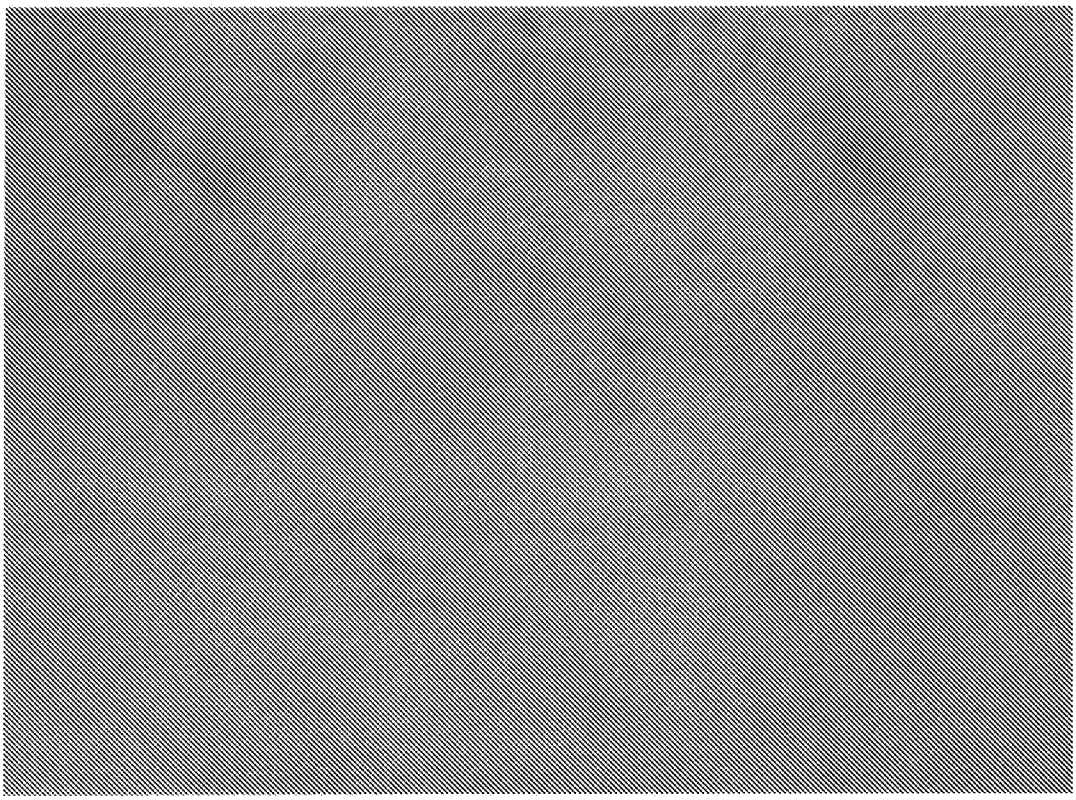


Figure 1a

Figure 1b

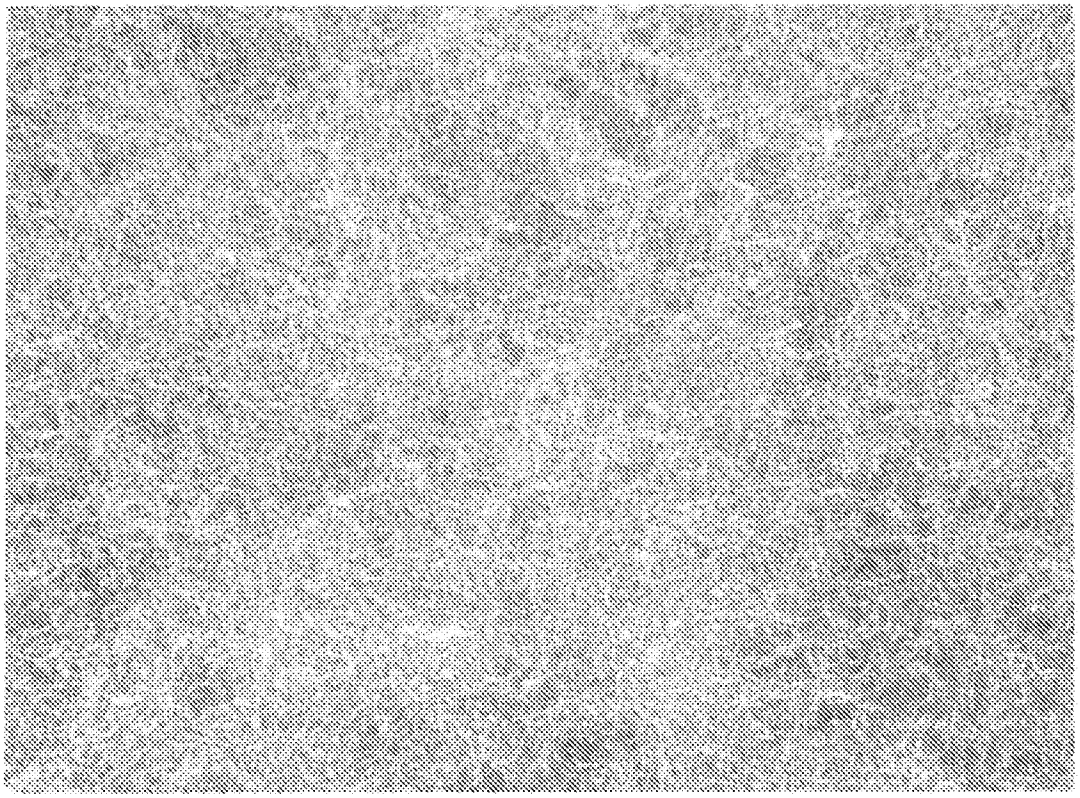


Figure 1c

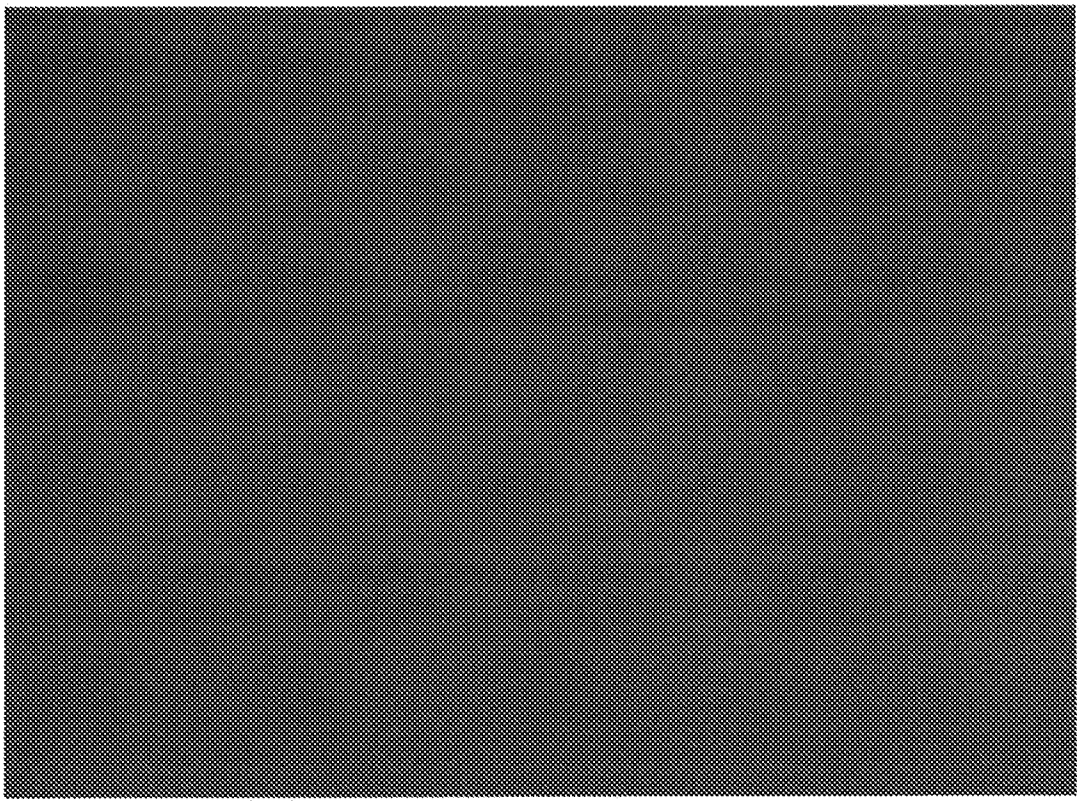


Figure 1d

Figure 2

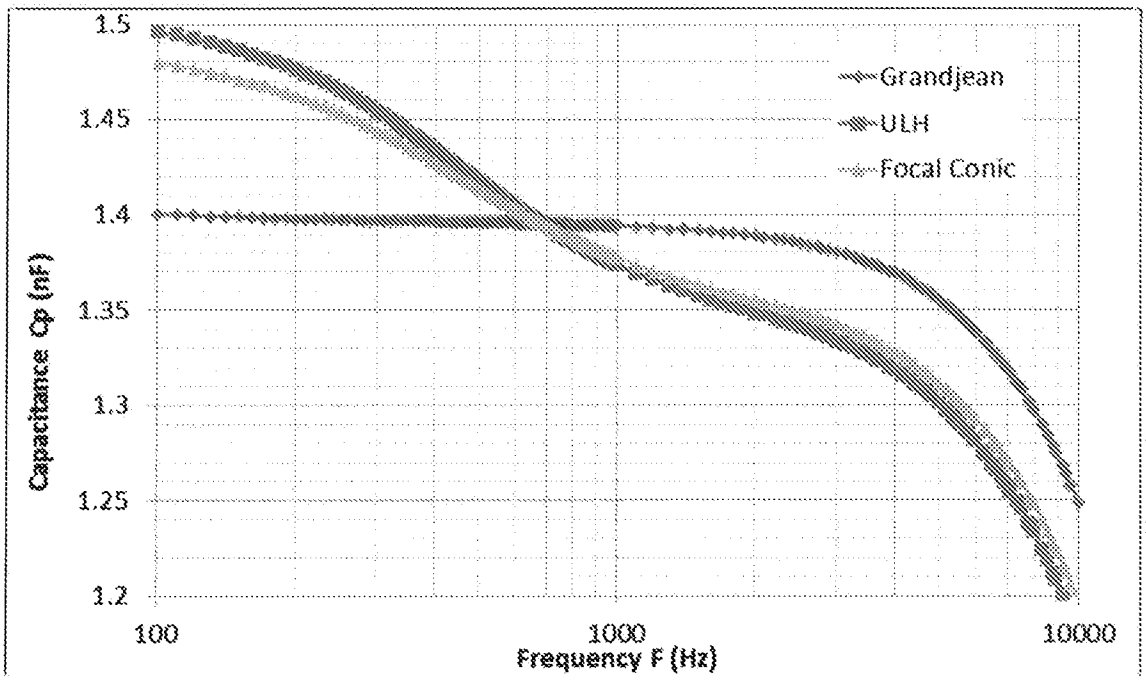

1.5
1.45
1.4
1.35
1.3
1.25
1.2
Capacitance Cp (nF)
100
1000
10000
Frequency F (Hz)
Grandjean
ULH
Focal Conic

Figure 3

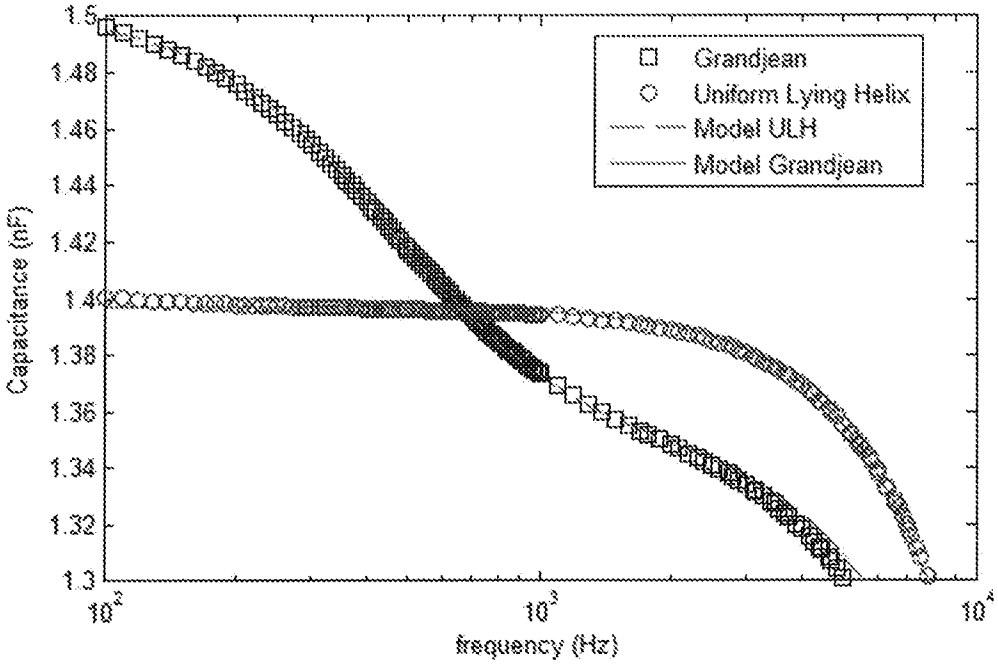


Figure 4

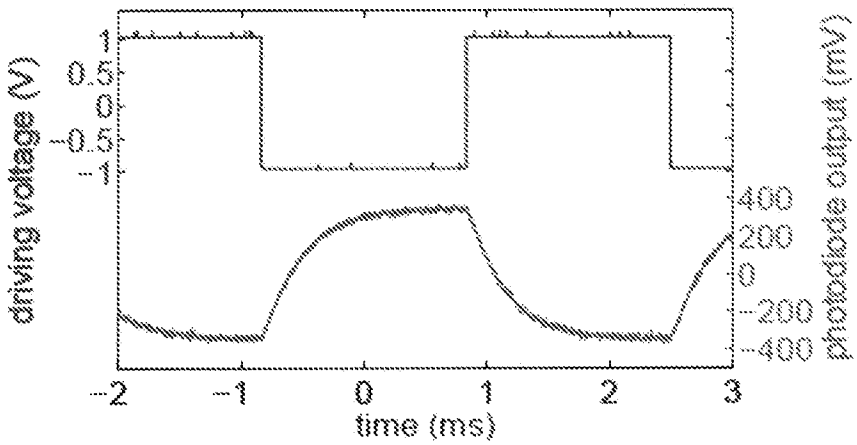


Figure 5

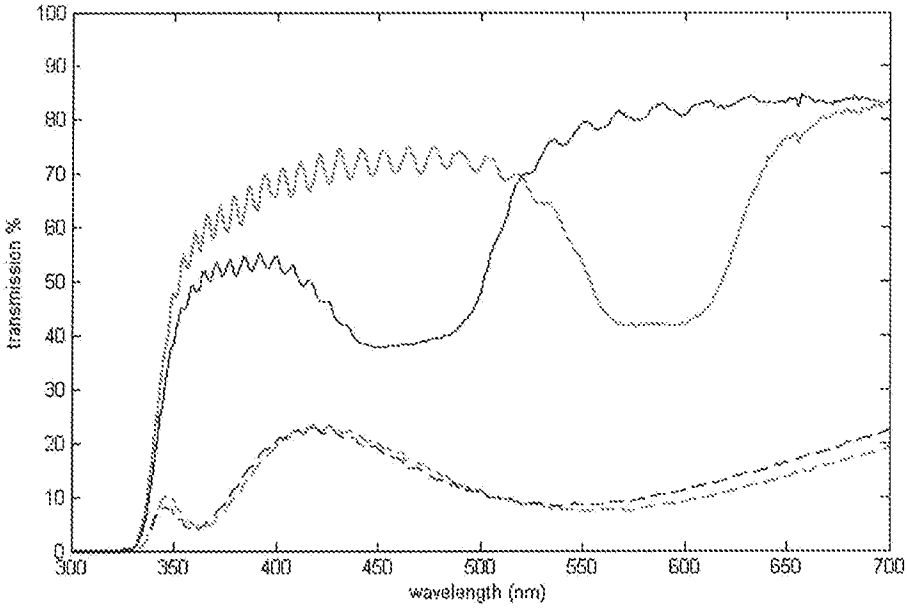


Figure 6

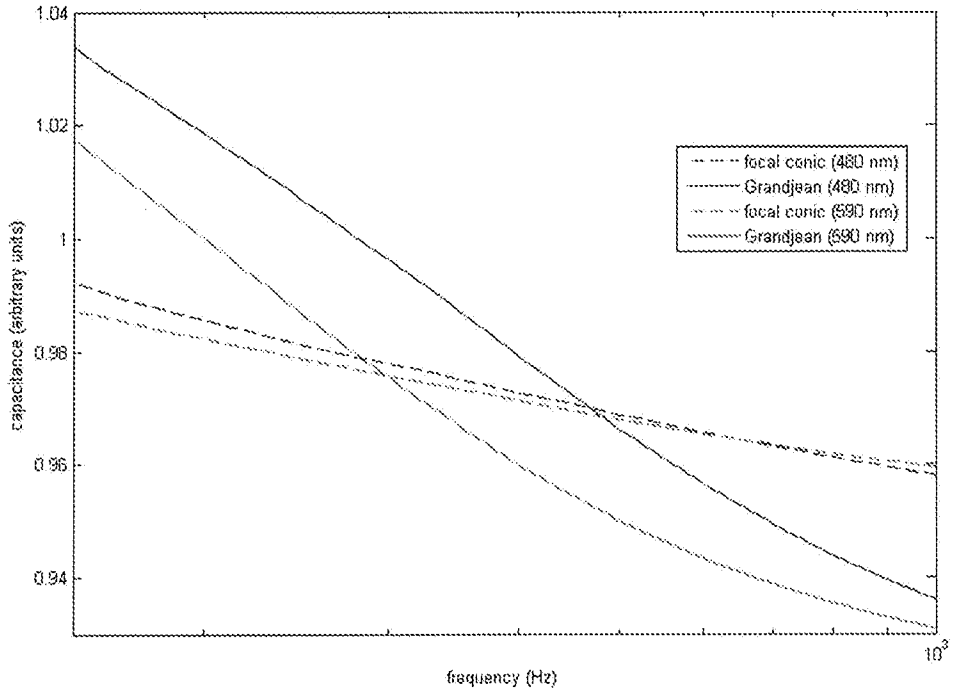


Figure 7

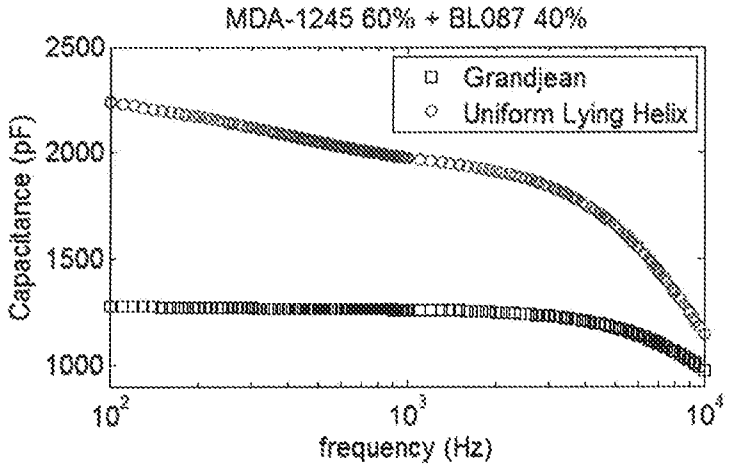


Figure 8

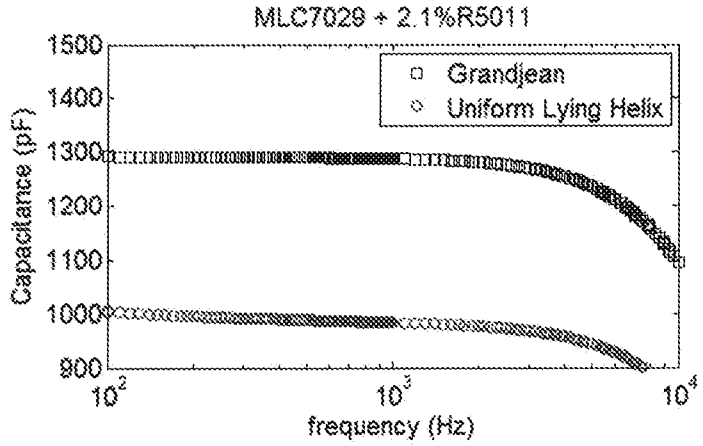
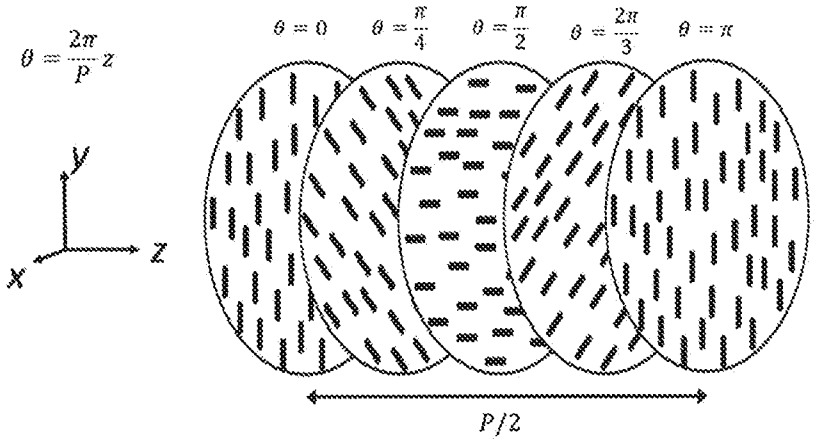


Figure 9



INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/050828

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02F1/137
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02F

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2006/003441 A1 (UNIV CAMBRIDGE TECH [GB]; COLES HARRY J [GB]; COLES MARCUS J [GB]; BRO) 12 January 2006 (2006-01-12) page 4, line 8 - page 9, line 28 page 14, line 5 - page 21, line 5 page 25, line 17 - page 29, line 17 figures 1-5,7,8,17-21 -----	1-20
A	US 2006/061720 A1 (CHEN WEI-CHOU [TW] ET AL) 23 March 2006 (2006-03-23) figures 1-5 paragraph [0003] - paragraph [0004] paragraph [0013] - paragraph [0022] -----	1-20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
2 June 2014	12/06/2014

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

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2014/050828

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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