Haze Free Reverse Mode Liquid Crystal Light Control Film with Inhomogeneous Alignment layer

Inventors: MC Tseng, CL Meng, ST Tang, HS Kwok, all of Hong Kong SAR

Assignee: Hong Kong University of Science and Technology

Abstract:

Provided is an electrically switchable light controlling device with transparent conductive layer on top and bottom substrates, inhomogeneous alignment surface layer, and a liquid crystal and polymer network middle layer in between. Small amount of polymerizable monomers are mixed with the liquid crystal and is cured to form polymer network. On top of both substrates, there are microscopic inhomogeneous surfaces on the alignment layers for scattering enhancement. The light controlling device is operating in a reverse mode such that a high transmission and haze free voltage off state and a highly scattered voltage on state is achieved.

Cited References:

U.S. Patent Documents

1. 3451741 6/1969 Manos
2. 5134833 6/1992 Barton et al
3. 4025163 5/1977 Saxe et al
4. 5463491 10/1995 Check, III
5. 4435047 3/1984 Fergason
6. 4688900 8/1987 Doane et al
7. 4994204 2/1991 Doane et al
8. 5056898 10/1991 Ma et al
9. 2008/0316395A1 12/2008 O'Keeffe
10. 6383577 B1 5/2002 Chidichimo et al
11. 7446830 B2 11/2008 Kim et al

Background of the Invention:

1. Field of the Invention:

The present invention deals with light controlling device by means of light scattering. The device is transparent when no voltage is applied. It scatters light efficiently upon the application of a suitable voltage. Such electrically switchable light controlling device can be applied to smart windows and transparent displays. The present device is based on a polymer - liquid crystal composite which is sandwiched in between conductive transparent substrates. Central to the invention is a special inhomogeneous alignment surfaces that can greatly enhance light scattering. Reverse mode operation with large viewing angle transparent voltage off state is achieved. Switchable windows are mainly used as architectural windows and indoor privacy windows. They are widely used in buildings, conference rooms, hotel rooms and potentially as vehicle windows.

2. Prior Arts

Commercially available electrically switchable windows can be divided into liquid crystal and non- liquid crystal types. Non-liquid crystal types include electrochromic (EC)[1,2] windows and suspended particle device (SPD)[3,4] windows. The EC windows switch from a voltage off clear state to a voltage on colored state. The typical light transmission range can be tuned from several percent to 50-70%. The switching time depends on the window size and can be as long as several minutes. The SPD windows has less than 1% light leakage in the dark state and has a switching time of 1-3 seconds. Due to the long switching time and light leakage problem, the EC and SPD windows are mainly applied to architectural windows and cannot be functioned as privacy windows. On the other hand liquid crystal based smart windows such as polymer dispersed liquid crystal (PDLC)[5,6] devices are able to switch from a transparent state to a scattering (diffused) state in milliseconds. The incident light is scattered rather than absorbed in the voltage on state. This highly scattered state is well suitable for working as privacy windows. However since PDLC devices cannot block light into the room, they are usually not preferred for architectural windows.

A typical commercial PDLC window works on the normally scattering (opaque) mode. It turns to a transparent state when a voltage is applied. The main drawbacks are 1. It is not normally clear so much electrical power is consumed to keep the window in the preferred clear state. 2. Due to the mismatch of refractive indices between the liquid crystal and polymer matrix, the clear state shows a very hazy view for large angle viewing 3. A high operating voltage is required (typically 50 volt or above).

Many attempts have been done to improve the above three main PDLC drawbacks.

In US patent 4994204 Doane et al[7] applied a birefringent polymer matrix such that the anisotropic optical properties of the polymer matrix is similar to that of the liquid crystal micro-droplets. A wider haze free viewing angles is achieved. Depending on the liquid crystal droplet configuration, normal mode or reverse mode operation is possible. However a significant drop of transmittance is still observed when viewing angle is larger than 45 degrees. Furthermore, the applied voltage is still at a high potential of 85 volts.

In US patent 5056898 Ma[8] et al proposed a reverse mode PDLC light shutter and display device. The reverse mode is obtained by modification of the surface energy of the polymer such that the major axis of the liquid crystals inside droplets oriented perpendicularly to the substrate and then the refractive index of the polymer matrix matches to the average refractive index of the liquid crystal. The result is a voltage off clear state. The off-axis haze is still significant, the transmission drops to about 60% at 45 degree viewing. The switching voltage is larger than 80 volts.

In US patent 2008/0316395A1 O'Keeffe[9] proposed a polymer dispersed cholesteric liquid crystal device (PDCLC) in which a much bigger liquid crystal droplets (preferably 3 to 17.5 microns) are formed. The cholesteric LC within each liquid crystal droplet is in polydomain structure. The scattering in the device is mainly due to the scattering between domains within the same droplet. When voltage is applied, all LCs are aligned in the device to give a haze free clear state. This PDCLC device is operating in a normal mode. The operating voltage is 50-60 volts.

In US patent 6383577 B1 Chidichimo[10] et al proposed a mutually dispersed liquid crystal and polymer device in which more than 50% by weight is monomers. The system is polymerized under an applied magnetic field if the monomers are not liquid crystal, otherwise no applied field is required. The result is an aligned liquid crystals dispersed in polymer. Since the liquid crystals are connected in a single domain, the voltage off state is transparent. The applied voltage for the scattering mode is larger than 50 volts.

In US patent 7446830 B2 Kim[11] et al proposed a method of aligning the liquid crystal with substrate surface treatment. Here polymer is aligned by polarized UV illumination during polymerization. The result is a horizontally aligned polymer immersed in homogeneously aligned liquid crystals. In voltage off state it is clear, when electric field is applied, the LC is disordered by the vertical aligned field and the horizontal aligned polymer.

In spite of the various research and development efforts, currently haze free reverse mode PDLC type smart window is still not commercially available.

A preferred switchable window device should have the following features:

1. Fast switching. Switching speed should be in millisecond range
2. Low operating voltage. Current PDLC smart windows has a rather high operating voltage (> 50 V).
3. Reverse mode operation. Glazing is in most case for transparent viewing, only at particular instants, opaque viewing is needed. Therefore a reverse mode operation is a preferred. It saves most of the operation energy when compare to normally opaque PDLC windows.
4. Haze free and wide viewing angle in clear state. It is a main drawback of current PDLC window that at larger oblique viewing angles, very hazy views are observed.
5. For outdoor applications, incident light intensity control is important. In addition other electromagnetic wave filtering functions, such UV and IR radiation filtering are desirable both for environmental protection and device lifetime consideration.

6. At last, bistable device that can stay in clear and opaque state without consuming power is the ultimate power saving device.

The present invention is providing an innovative solution to the above 1-5 features.

Summary of the Invention:

One aspect of the present invention is to provide a reverse mode light controlling device. That means it has a powerless normally clear state and an opaque voltage on state. In contrast the current polymer dispersed liquid crystal (PDLC) device operates in a normal mode. In the voltage off state incident light is scattered due to the mismatch of the refractive index in the polymer matrix and the liquid crystal. When the voltage is on, there exists a vertically aligned electric field between the top and bottom conductive substrates. The liquid crystals are forced to align with the electric field. Since the ordinary refractive index of the liquid crystals is chosen to match the refractive index of the polymer matrix, therefore the scattering is minimized for normal viewing and this is the clear state. As liquid crystal is a birefringent material, the extraordinary refractive index becomes effective when light is coming from oblique angles, and refractive index mismatch becomes significant. This inherent haze increases with large viewing angles even it is in the clear state.

In our present invention we first apply a much less percentage of polymer in the liquid crystal – polymer mixture. Instead of a continuous polymer matrix and separate liquid crystal droplets formation, there forms a polymer network immersed in liquid crystals, it is sometimes referred to as polymer network liquid crystal (PNLC) structure or polymer stabilized liquid crystal (PSLC) device. Second a homeotropic surface alignment layer is applied to align the liquid crystals in a vertical direction in the voltage off state. Third negative type liquid crystal that has a negative dielectric anisotropy is used such that when it is under a vertical electric field, the liquid crystal molecules tend to align perpendicularly to the electric field. Fourth we have polymer network that has a refractive index close to that of the liquid crystal such that when in the voltage off state, there is minimum light scattering for all viewing angles.

In another aspect of the present invention, we have deliberately enhanced the inhomogeneity of the alignment layer. Polymer structures are embedded into the liquid crystal alignment material to form an inhomogeneous alignment layer. This layer serves at least two purposes, first to align the liquid crystals homeotropically in the voltage off state; second to promote the liquid crystal alignment randomness in the voltage on state.

The operation of the present reverse mode PNLC window can be as follows:

1. In the voltage off state, the liquid crystals are aligned vertically and so do the polymer network. Since the refractive indices of the liquid crystals are close to that of the polymer network, the device is in a transparent state. The matching of the refractive indices do not change with viewing angle, therefore a large viewing angle haze free transparent state is achieved.

2. When there is an applied voltage, the negative type liquid crystal molecules tend to re-orient and deviate from the vertical aligned position.
3. The liquid crystals only start to re-orient when the applied voltage is beyond a certain threshold voltage. Due to the inhomogeneous alignment surface and the polymer network in bulk, many randomly aligned LC domains are formed and it is the scattering state.
4. The scattering increases when the voltage increases and reach a maximum. And sometimes the scattering may start to drop if excessive voltage is applied.
5. When the applied voltage is turned off, the liquid crystals return to their original vertical alignment and the device is clear again.

The inhomogeneous alignment surface plays a central role in promoting the scattering in this device.

Yet follow the same physical concept of inhomogeneous alignment surface and polymer network liquid crystals, homogeneous (planar) aligned liquid crystals with positive dielectric anisotropy can also be applied. In that case a reverse mode operation can also be achieved and homeotropic alignment material is not needed.

Brief Description of the Drawings:

Fig. 1 shows the basic structure of the reverse mode PNLC including **10** Substrate with transparent conductive coating layer; **20** Inhomogeneous alignment layer; **30** Spacer structure; **40** Liquid crystal with polymer network layer.

Fig. 2 shows the Atomic Force Microscope picture of the inhomogeneous surface alignment layer **20**.

Fig. 3 shows a line profile of the inhomogeneous layer.

Fig. 4 shows the liquid crystal alignment **50** near the inhomogeneous alignment layer.

Fig. 5 shows when the device is connected to a voltage supply **60** and it is in a voltage off state. Light **70** pass through the device with minimum scattering.

Fig. 6 shows when there is an operating voltage. Light incident on the random LC domain and is scattered **80**.

Fig. 7 is an example of the transmittance voltage curve of present invention. A low voltage operation is shown.

Fig. 8 shows the liquid crystal planar alignment **90** when positive dielectric anisotropic liquid crystal is used. In the voltage off state light pass through with minimum scattering.

Fig. 9 shows that when the device in fig.8 is in the voltage on state, the positive liquid crystals tend to align vertically and forms domain with different liquid crystal orientations. This is the scattering state **100**.

Fig. 10 shows a dichroic dye **110**, it absorbs light along the long axis of the dye molecule but allow light in orthogonal direction to pass through. In voltage off state, normal incident light pass through without significant absorption.

Fig. 11 shows that when the device in fig.10 is in the voltage on state, the random domains formed absorb light from all directions **120**. Complete absorption is in fact not by single dye, but by many dye molecules in multiple absorptions.

Fig. 12 shows the possible effects of the switchable window on viewing. **130** transparent voltage off state; **140** opaque scattering state with diffused light coming through; **150** opaque absorption state with minimum light coming through.

Fig. 13 shows a patterned switchable window. At the top right corner a patterned area can show diffused pattern (voltage on) **160** with clear background (voltage off) or reverse **170**.

Fig 1.

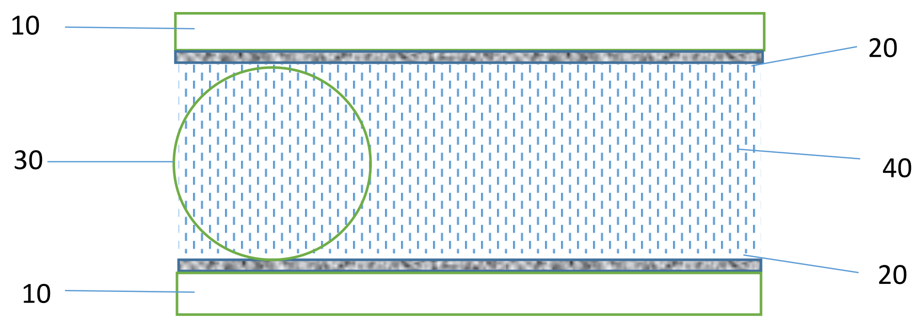


Fig.2

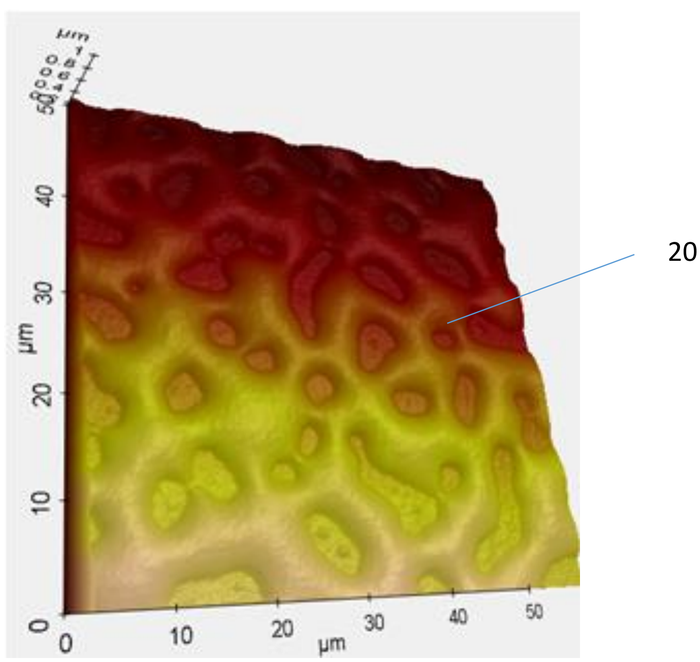
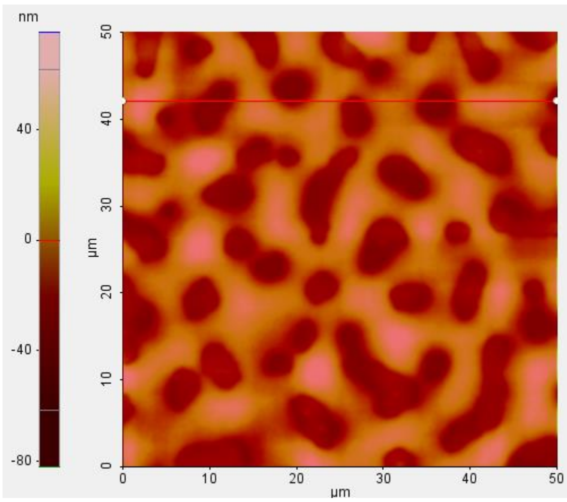


Fig.3



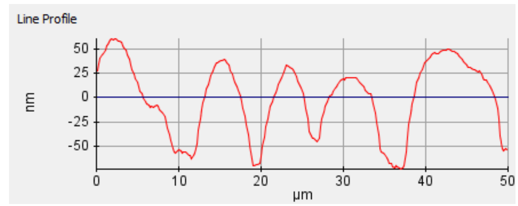


Fig. 4

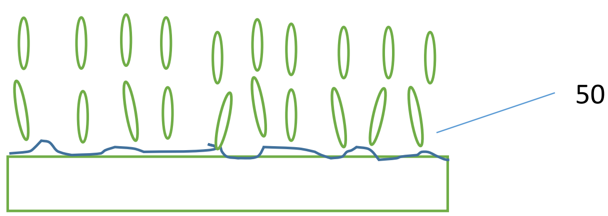


Fig. 5

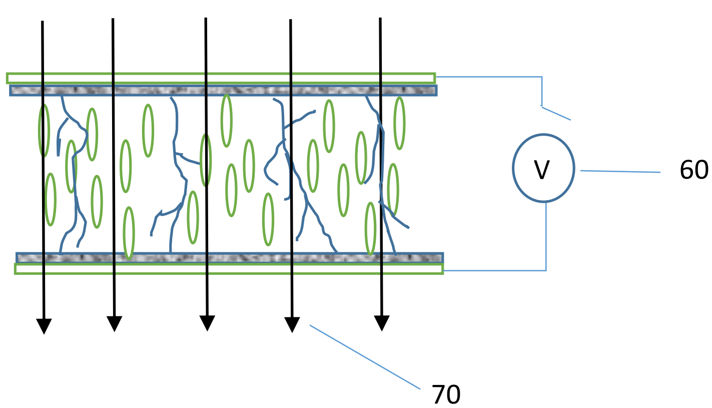


Fig.6

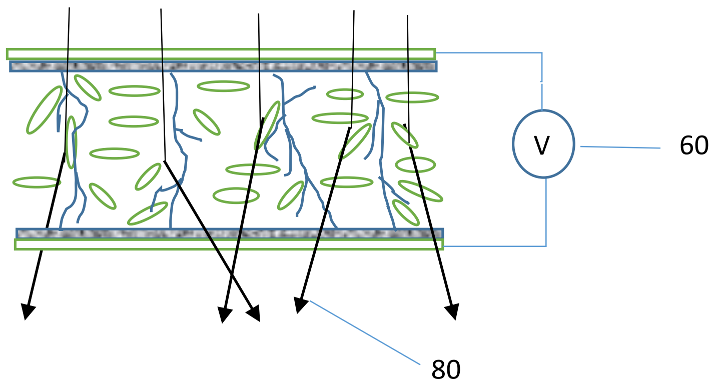


Fig. 7

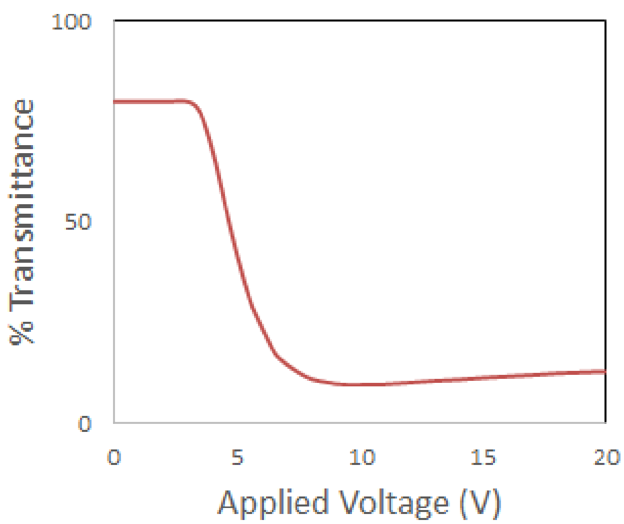


Fig. 8

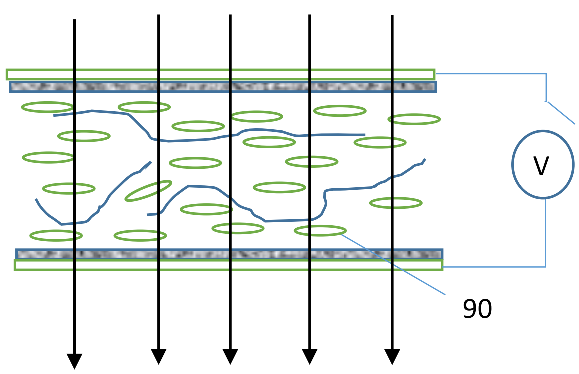


Fig. 9

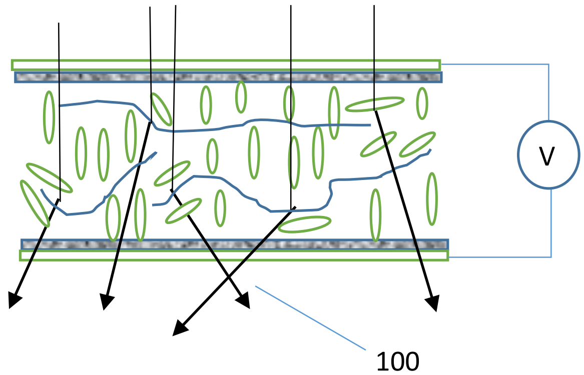


Fig. 10

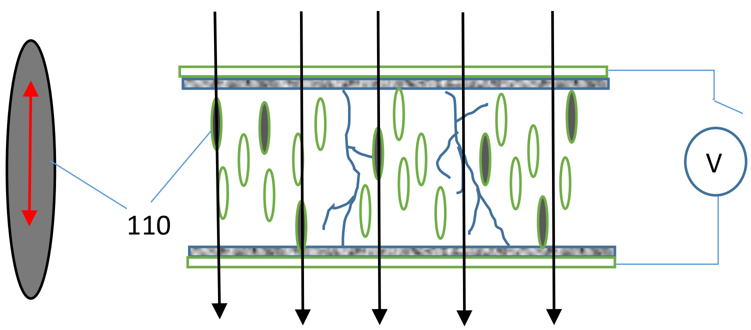


Fig. 11

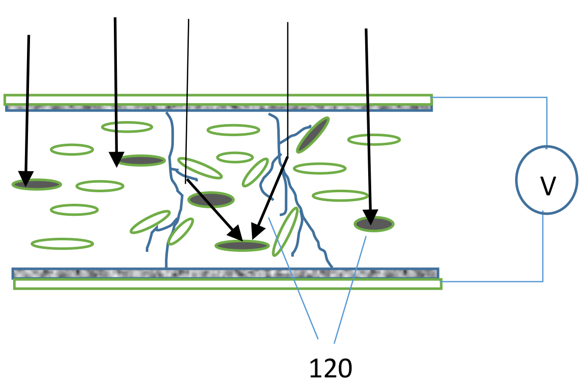


Fig. 12

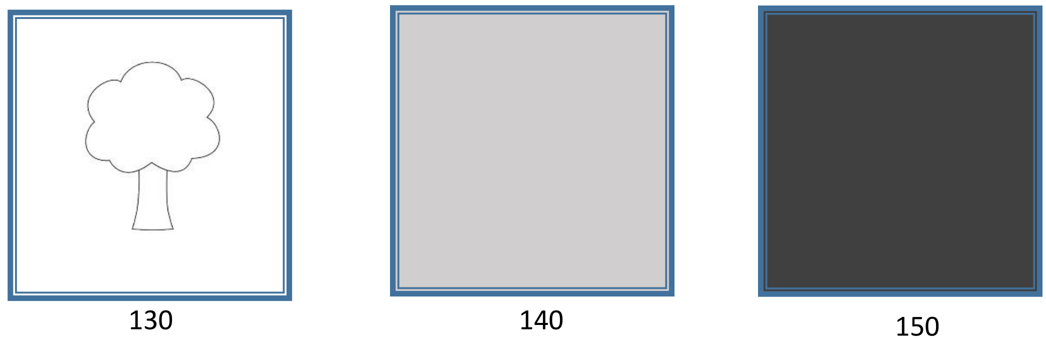
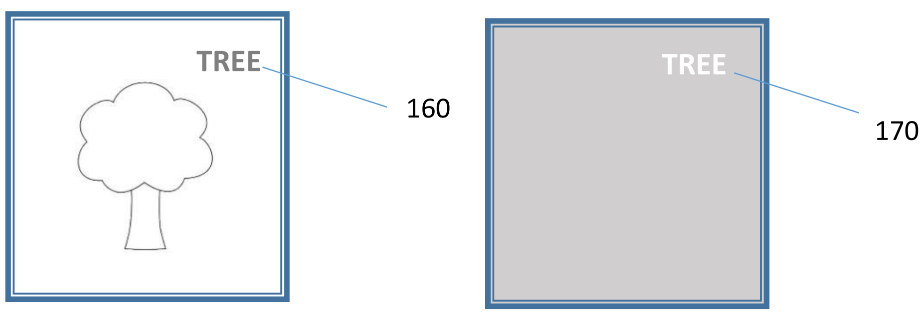


Fig. 13



Detail Description of the Invention:

In the present invention, a light controlling device with normal clear transparent state and voltage on scattering or opaque state is disclosed. This reverse mode light controlling device may be used as switchable window or shutter or transparent display.

The basic structure of the device is as shown in Fig.1. The top and bottom are substrates with transparent conductive electrodes **10**. The substrates can be indium tin oxide on glass or other transparent conductive coating on glass or plastic substrates. Both substrates are coated with an inhomogeneous alignment layer **20**. The distance between the two substrates is determined by the spacers **30** in between the two substrates. The gap between the two substrates is filled with liquid crystals with a polymer network **40** formed during fabrication.

If the substrates are flexible plastics, in practice the device as described in Fig. 1 can be sandwiched in between glasses in architectural or privacy window applications. In addition the glass substrates or the external glasses (for plastic substrates) may have other functional coatings such as UV cut, IR cut and so on.

In one embodiment the alignment layer is made of homeotropic alignment material with addition of a few percent of reactive mesogen. The function of the homeotropic alignment material is to align the liquid crystals in a vertical orientation during the voltage off state. Addition of the reactive mesogen is to create an inhomogeneous rough surface. The polymerization of the reactive mesogen forms local inhomogeneity on the alignment layer (Fig.2). The layer has a profile depth of around 100 nanometers and domain size of several to tenths micrometers (Fig. 3).

The function of the inhomogeneous surface is 1. to give small polar and random azimuthal angle to the vertically aligned liquid crystal molecules (Fig.2); 2. to enhance the formation of polymer network on the substrate surface and hence strengthen the adhesion between substrates. Example of homeotropic alignment layer is SE-4811 vertical alignment material from Nissan Chemical Industries. Reactive mesogen is UCL 017 from DIC.

The inhomogeneous alignment surface can be formed in a single layer by mixing the alignment material with the reactive mesogen in a homogenous solution. The solution is then coated on the substrates and the reactive mesogen is cured and an inhomogeneous surface is formed.

Yet the inhomogeneous alignment surface can also be formed in two layers, first the homeotropic alignment layer then the reactive mesogen layer.

Yet it is also possible to coat the reactive mesogen layer before the homeotropic alignment layer.

In all cases the amount of reactive mesogen used and the curing condition directly affect the inhomogeneity and profile of the layer.

Yet it is also possible to form the inhomogeneous alignment surface by adding other kinds of monomers or small particles or directly coats the alignment layer on rough transparent conductive layer surface without the use of addition monomers.

At last inhomogeneous alignment layer can also be formed by random aligned or multiple aligned surface.

For the present invention, the middle layer is filled with liquid crystals and monomers. Liquid crystal to monomer ratio by weight is usually less than that of conventional polymer dispersed liquid crystal (PDLC) device. It is in most cases, less than 10% monomer by weight. The liquid crystal and monomer mixture is cured by suitable condition and polymer network is formed in the bulk of the middle layer (Fig. 5). Example of monomer used is UCL 017 from DIC. Liquid crystal is index matched negative nematic liquid crystals. Small amount of photo-initiator is also added to promote the polymerization of monomers.

As shown in Fig.5 the liquid crystals are aligned homeotropically and there is a polymer network formed. The choice of polymer here is to match the refractive index of the liquid crystal and polymer. Since liquid crystal is a birefringent material with ordinary and extra-ordinary index, we prefer to use liquid crystal polymer to minimize the clear state scattering. With a good matching of refractive indices, a large viewing angle voltage off clear state can be achieved.

When there is an applied voltage (Fig.6), an electric field is set up in the device. Since the liquid crystal has a negative dielectric anisotropy, the liquid crystal molecules tend to align perpendicularly to the electric field. That means the original vertically aligned liquid crystals want to rotate to a horizontal position.

The liquid crystals that are not near the inhomogeneous alignment surface or the polymer network rotate to the horizontal position first. The liquid crystals near the surface has a strong anchoring force that hinders the molecular rotation, furthermore the random surface inhomogeneity gives a random azimuthal angle to the liquid crystal molecules. In addition the polymer network in the bulk also hinders the rotation of the liquid crystal molecules. As a result there forms many small liquid crystal domains with different liquid crystal orientations. There are liquid crystal domain-domain scattering and liquid crystal – polymer network scattering. Finally a diffused state is achieved. Fig. 7 shows a typical transmission voltage curve, a low operation voltage is obtained.

Yet in another embodiment, no homeotropic alignment material is used, the liquid crystal with positive dielectric anisotropy is aligned in a homogeneous or planar way (Fig. 8) in voltage off state. This is the clear state. When voltage is switched on, a vertical electric field is setup in between the two substrates. The liquid crystal molecules tend to align with the electric field. Because of the hindrance of the surface inhomogeneity and polymer network liquid crystal domains formed and this is the scattering state (Fig. 9).

Yet in another embodiment dichroic dyes are added into the negative dielectric liquid crystal polymer network layer. Example of dye used is a black dye S428 from Mitsui Fine Chemicals, but any other dichroic dyes are equally applicable. The dichroic dye molecules are in elongated shape and are following the alignment direction of neighboring liquid crystals. When the device is in voltage off state (Fig. 10) the dyes being vertically aligned, do not absorb normally incident light and thus the device is still transparent as in the no dye case, but for oblique viewing the dye absorbs some light and thus the transmission is lower.

When the device is in the voltage on state (Fig. 11) the random aligned liquid crystal domains with dyes absorb light from all incident angles, thus an opaque dark state is obtained.

The reverse mode polymer network inhomogeneous surface liquid crystal light controlling device is well suitable for smart glazing or privacy window applications (Fig 12). The dye doped version can be applied to architectural windows where light transmission control is desirable. It is also well suitable for use as an integral part of emission transparent display that lacks a true dark state.

At last one can always have the transparent conductive layer patterned to drive pixel by pixel. Or combined with an active matrix device to become active matrix driven smart display. One embodiment is to make simple text or clock pattern in the substrate as shown in Fig.13 **160**, **170**.

The invention as presented herein and the specific aspects or embodiments illustrated or material used in examples are meant not to be limiting, but may include variations, modifications or adaptations pertaining to the principle of current invention. As noted all drawings presented are not drawn to scale nor are exact replicate of real devices.

What is claimed is:

1. An electrically switchable light controlling device comprising:
    - two transparent substrates coated with transparent conductive layer;
    - an inhomogeneous alignment layer for the alignment of liquid crystal molecules disposed on top of each transparent conductive layer where the inhomogeneity consists of distinct regions of different materials having different topography;
    - spacers to keep the two substrates in a predetermined separation distance;
    - a liquid crystal layer in between the two said substrates;
    - a polymer network disposed inside the said liquid crystal layer;

2. The liquid crystal layer in claim 1 being aligned homeotropically or homogeneously to give an almost transparent voltage off state while it forms micro domains to give a scattering voltage on state.

3. The device of claim 1, wherein the transparent conductive substrates are made of glass or flexible plastic. One embodiment is indium tin oxide on glass, yet another embodiment is indium tin oxide on Polyethylene Terephthalate (PET) film or other transparent plastic material.

4. The device of claim 1, wherein the alignment layer comprises of a kind of homeotropic alignment material such that the liquid crystal molecules near the alignment layer can keep a vertical alignment orientation.

5. The device of claim 1, wherein the alignment layer is created by mixing the homeotropic alignment solution with reactive mesogen or monomers or other sub-micron particles and coated in a single layer. The coated alignment layer is cured under controlled conditions to form the inhomogeneous alignment layer.

6. The device of claim 1, wherein the surface alignment layer is coated with homeotropic alignment layer and reactive mesogen or monomer or sub-micron particle layer in two stacks.

7. The device of claim 1, wherein the surface alignment material is a kind homogenous or planar alignment material.

8. The device of claim 1, wherein the inhomogeneous alignment layer does not contain any specific alignment chemical.

9. The device of claim 1, wherein the inhomogeneous alignment layer is a random aligned or multi- directions aligned layer.

10. The device of claim 1, wherein the reactive mesogen or monomers mixed in alignment layer is polymerized under UV radiation or suitable temperature.

11. The device of claim 1, wherein the inhomogeneous surface is formed by coating the alignment material directly on an inhomogeneous conductive transparent surface without adding extra monomer/ polymer.

12. The device of claim 1, wherein the liquid crystal is a kind of negative dielectric liquid crystal such that when voltage is applied, the liquid crystal molecules tend to align perpendicular to the electric field direction.

13. The device of claim 1, wherein the polymer network is formed by UV or thermal curing to polymerize a kind of liquid crystal monomer or reactive mesogen or other kind of monomers.

14. The device of claim 1, wherein the liquid crystal is mixed with dichroic dyes. When dichroic dyes are introduced, the device works by switching between a clear voltage off state and an absorptive or dark voltage on state.

15. The device of claim 1, wherein the spacers for determining the separation of the two conductive transparent substrates is made of glass or plastic rods or beads and is dispersed into the liquid crystal polymer composite.

16. The device of claim 1, wherein the spacers are built-in structures such as cylinders or bumps on top of the transparent conductive substrates by photo-etching or screen printing or other technologies.

17. The device of claim 1, wherein the transparent conductive layer is patterned, so that different parts of the devices can be in voltage on and voltage off state independently.

18. The said transparent conductive layer in claim 1 being connected to electrodes for and to external circuits for electrical driving.

19. The device of claim 1, wherein one of substrate is an active matrix thin film transistor (TFT) backplane, so that the device can be actively driven pixel by pixel.

20. A smart architectural window comprising the device of claim 1. One embodiment is the device of claim 1 with ITO on PET film substrates coated with liquid crystal polymer network and sandwiched between architectural glass that are coated with low-E coating and/ or other functional thin film coatings.

21. A smart privacy window used indoor comprising the device of claim 1.

22. A smart window applied in vehicles comprising the devices of claim 1.

23. A transparent display component comprising the device of claim 1 and/ or claim 14.

24. A projection screen comprising the device of claim 1.

25. A touch screen or device comprising the device of claim 1.

26. A smart window device comprising more than one piece of the device of claim 1 stacked together.