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(71) Applicant: **AGENCY FOR SCIENCE, TECHNOLOGY AND RESEARCH** [SG/SG]; 1 Fusionopolis Way, #20-10, Connexis North, Singapore 138632 (SG).

(72) Inventors: **SURESH, Vignesh**; c/o Institute of Materials Research and Engineering, 2 Fusionopolis Way, #08-03, Innovis, Singapore 138634 (SG). **ONG, Kian Soo**; c/o Institute of Materials Research and Engineering, 2 Fusionopolis Way, #08-03, Innovis, Singapore 138634 (SG). **CHEW, Ah Bian**; c/o Institute of Materials Research and Engineering, 2 Fusionopolis Way, #08-03, Innovis, Singapore 138634 (SG). **TAN, Yuan Ling, Christina**; c/o Institute of Materials Research and Engineering, 2 Fusionopolis Way, #08-03, Innovis, Singapore 138634 (SG). **LOKE, Yee Chong**; c/

o Institute of Materials Research and Engineering, 2 Fusionopolis Way, #08-03, Innovis, Singapore 138634 (SG).

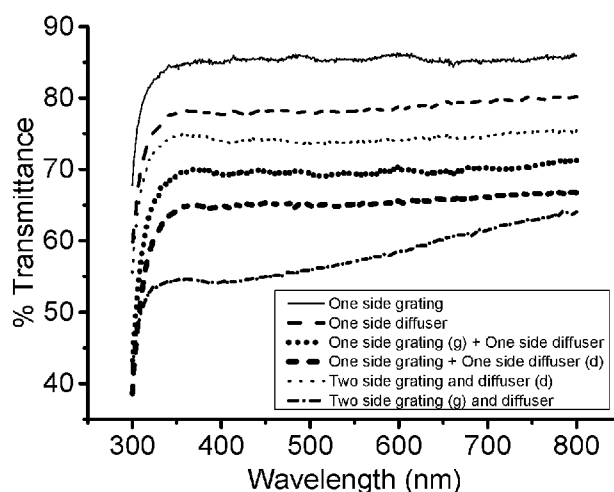
(74) Agent: **PATEL, Upasana**; Marks & Clerk Singapore LLP, Tanjong Pagar Post Office, P.O. Box 636, Singapore 910816 (SG).

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(54) Title: A METHOD OF CONTROLLING LIGHT INTENSITY

Figure 4A



(57) Abstract: A method of controlling light intensity There is provided a method of controlling intensity of visible light, the method comprising passing visible light through an optical plastic film, wherein the optical plastic film comprises at least one functional surface that controls the intensity of the without the use of electricity.



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A method of controlling light intensity

Technical Field

The present invention relates to a method of controlling intensity of visible light.

5 Background

Many optical films function as light guides, wave guides and back lights. Simply, they function to direct or channel the light in a specific direction.

For example, in an indoor farm, the growth of plants is dependent on the overall lighting efficiency, which in turn is dependent on the light spectrum, intensity, photoperiod and
10 useful light available for photosynthesis. While there are variety of lighting schemes for indoor farms, light-emitting diode (LED) technology is a key grow-light technology used in many commercial farms. Most LED based grow-lights have micro-controllers and drivers to control the intensity so as to provide plants with appropriate energy for their growth. As the LEDs are electrically controlled, their spectrum is adjusted to desired
15 intensity to suit the stage of plant growth. Variation in the intensity of light at source using drivers and microcontrollers that are electrically powered are expensive, consume more energy and more heat is generated indoors.

There is therefore a need for an improved method of providing controlled transmission of visible light.

20 Summary of the invention

The present invention seeks to address these problems, and/or to provide an improved method of providing controlled transmission of visible light.

According to a first aspect, there is provided a method of controlling intensity of visible light, the method comprising: passing visible light through an optical plastic film, the
25 optical plastic film comprising at least one functional surface that interacts with incident visible light to control the intensity of the incident visible light by transmitting 50-90% of the incident visible light without the use of electricity.

In particular, the method enables a pre-determined wavelength of the visible light to be transmitted through the optical plastic film.

The at least one functional surface may be formed by any suitable method. According to a particular aspect, the at least one functional surface may be formed on the at least one optical plastic film by nanoimprint lithography.

5 The at least one functional surface may comprise any suitable feature to form the functional surface. For example, the at least one functional surface may comprise, but is not limited to, diffuse surface, grating surface, three-dimensional patterning, or a combination thereof.

10 According to a particular aspect, the at least one functional surface may comprise a grating surface. In particular, the grating surface may comprise grating structures having a pre-determined grating width, gap and height. The pre-determined grating width, gap and height may be any suitable width, gap and height. For example, the pre-determined grating width may be 3-8 μm , the pre-determined gap may be 3-7 μm and/or the pre-determined height may be 3-8 μm .

15 According to a particular aspect, the at least one functional surface may comprise three-dimensional patterning. For example, the three-dimensional patterning may be any suitable patterning. In particular, the three-dimensional patterning may comprise pyramid structures, inverse pyramid structures, or a combination thereof.

20 In particular, the optical plastic film may comprise two functional surfaces. For example, the two functional surfaces of the optical plastic film may comprise a diffuse surface and a grating surface, respectively.

The optical plastic film may be formed from any suitable material. For example, the optical plastic film may be formed from, but not limited to, polycarbonate.

25 According to a particular aspect, the optical plastic film may be provided on an optical panel. In particular, the optical panel may comprise a plurality of the optical plastic films, wherein each of the plurality of the optical plastic films may comprise the same or different functional surface from the other. Even more in particular, the optical panel may provide transmission of the visible light of different intensities across the spectrum of wavelength of the visible light based on the functional surface comprised on each of the plurality of optical plastic films.

Brief Description of the Drawings

In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments, the description being with reference to the accompanying illustrative drawings. In the drawings:

Figure 1A shows the image obtained from the confocal laser scanning microscope of a Ni mold with gratings used for imprinting PC sheets and Figure 1B shows the top view of a Ni mold that imparts a diffuse surface when imprinted on PC sheets;

Figure 2A shows one-side imprinting of the polycarbonate thin sheets using Ni grating mold; Figure 2B shows one-side imprinting of the polycarbonate thin sheets using Ni mold that imparts light diffusing effect upon imprinting and Figure 2C shows two-side (double-sided) imprinting of PC thin sheet using Ni molds on either sides of the sheet;

Figure 3 shows the schematic representation of a set-up of different imprinted sheets for % transmittance measurements. Figure 3A shows set-up in which a PC imprint with grating structure and a PC imprint with a light diffusing structure are arranged in series with the gratings structure facing the light source; Figure 3B shows set-up in which a PC imprint with grating structure and a PC imprint with a light diffusing structure are arranged in series with the diffusing structure facing the light source; Figure 3C and Figure 3D show the set-up of a double-sided imprint with the grating side and diffusing side facing the light source, respectively;

Figure 4A shows the % transmittance of the polycarbonate sheet imprinted with different structures (grating and diffusing) in different configurations and their arrangement while measuring their %T. Figure 4B shows the % transmittance of the control blank PC. The letter within parenthesis in the legend represents the corresponding imprint sample ('d' for diffuser and 'g' for grating) that directly faces the light source;

Figure 5 shows a schematic representation of the use of an optical panel according to one embodiment;

Figure 6A shows the SEM image of a PC sheet imprinted with pyramid structures and Figure 6B shows a PC sheet imprinted with inverse pyramid structures; and

Figure 7 shows the % transmittance of a PC sheet imprinted with pyramid and inverse pyramid structures.

Detailed Description

As explained above, there is a need for an improved method to control intensity of the visible light and providing a more controlled method of the transmittance of visible light.

In general terms, the present invention provides a method of controlling the intensity of visible incident light using optical films, but without the use of electricity. This may be useful in many applications, such as, but not limited to, indoor farming, in which specific range of wavelengths of the visible light are more useful than others as energy sources for photosynthesis. In particular, the method utilises optical plastic films which avoids the use of microcontrollers and LED drivers, while still being able to provide good control over transmission variation between 50-90% of the incident visible light.

The method described herein is cheaper and more environmentally friendly since it does not require the use of electricity. This also avoids unnecessary heating due to loss of energy in the form of heat by alternatives which comprise artificial lighting systems.

According to a first aspect, there is provided a method of controlling intensity of visible light, the method comprising: passing visible light through an optical plastic film, the optical plastic film comprising at least one functional surface that interacts with incident visible light to control the intensity of the incident visible light by transmitting 50-90% of the incident visible light without the use of electricity.

The method enables the control of the intensity of the incident visible light by transmitting 50-90% of the incident visible light. In particular, the control results in transmitting 55-85%, 60-80%, 65-75%, 70-72% of the incident visible light.

In particular, the method enables manipulation of light intensity. For example, the method enables a pre-determined wavelength of the visible light to be transmitted through the optical plastic film. For example, it is established that specific range of wavelengths of the visible light spectrum at blue (400–500 nm) and red (600–700 nm) are considered to be major energy sources for photosynthesis. According to a particular aspect, the method enables specific uniform amount of light to be transmitted

through the optical plastic film. This is currently generally achieved by microcontrollers. However, the method unexpectedly enables the control to be achieved without the use of microcontrollers or drivers.

The optical plastic film may be formed from any suitable material. For example, the optical plastic film may be formed from any suitable plastic material such as, but not limited to, polycarbonate (PC), polystyrene (PS), polyethylene terephthalate (PET), copolymers or blends thereof. In particular, the optical plastic film may be formed from PC.

The at least one functional surface may comprise any suitable feature to form the functional surface. For example, the at least one functional surface may comprise, but is not limited to, diffuse surface, grating surface, three-dimensional patterning, or a combination thereof.

The diffuse surface may comprise suitable diffuse structure which enable light to be diffused when incident on the diffuse surface. For example, the diffuse surface may comprise any suitable diffuse structures such as roughened surfaces, matt finish, or a combination thereof.

The grating surface may comprise grating structures which enable incident light to be scattered. The grating surface may be formed by any suitable grating structures. In particular, the grating surface may comprise grating structures having a pre-determined grating width, gap and height. The pre-determined grating width, gap and height may be any suitable width, gap and height. For example, the pre-determined grating width may be 3-8 μm , 3.5-7.5 μm , 4-7 μm , 4.5-6.5 μm , 5-6 μm , 5.5-6 μm . In particular, the grating width may be 4.5-5.5 μm . The pre-determined gap may be 3-7 μm , 3.5-6.5 μm , 4-6 μm , 4.5-5.5 μm , 5-5.3 μm . In particular, the gap may be 3.5-5 μm . For example, the pre-determined grating height may be 3-8 μm , 3.5-7.5 μm , 4-7 μm , 4.5-6.5 μm , 5-6 μm , 5.5-6 μm . In particular, the grating height may be 4.5-5.5 μm .

According to a particular aspect, the at least one functional surface may comprise three-dimensional patterning. The three-dimensional patterning may be any suitable patterning and may comprise three-dimensional structures. In particular, the three-dimensional structures may comprise pyramid structures, inverse pyramid structures, or a combination thereof. The three-dimensional structures may be of a suitable size.

For example, the three-dimensional structures may have at least one side of dimension 100-1000 nm. In particular, the three-dimensional structure may have at least one side having a dimension of 150-900 nm, 200-800 nm, 250-750 nm, 300-700 nm, 350-650 nm, 400-600 nm, 450-550 nm, 500-525 nm. Even more in particular, the dimension
5 may be 650-800 nm . The three-dimensional structures may be spaced from one another. The spacing between each three-dimensional structure may be equal or random and may be of a suitable spacing. For example, the spacing between each three-dimensional structure may be 10-200 nm, 15-175 nm, 25-150 nm, 50-125 nm, 75-100 nm. In particular, the spacing may be 75-125 nm.

10 The optical plastic film may comprise two surfaces. The functional surface may be provided on either or both surfaces of the optical plastic film. Accordingly, the optical plastic film may comprise a one-sided surface functionalised optical plastic film or a two-sided surface functionalised optical plastic film. In particular, when the optical plastic film is a two-sided surface functionalised optical plastic film, each of the two
15 sides of the optical plastic film may be functionalised in the same or different manner. According to a particular aspect, each of the two sides of the two-sided surface functionalised optical plastic film may comprise a first functional surface on one side and a second functional surface on the other side, wherein the first functional surface and the second functional surface comprise different features forming the functional
20 surface. In particular, a two-sided surface functionalised optical plastic film may comprise a diffuse surface on one side of the optical plastic film and a grating surface on the other side of the optical plastic film, respectively.

The at least one functional surface may be formed by any suitable method. According to a particular aspect, the at least one functional surface may be formed on the at least
25 one optical plastic film by nanoimprint lithography.

According to a particular aspect, the optical plastic film may be provided on an optical panel. In particular, the optical panel may comprise a plurality of the optical plastic films, wherein each of the plurality of the optical plastic films may comprise the same or different functional surface from the other.

30 The plurality of optical plastic films may comprise one-sided surface functionalised optical plastic film, two-sided surface functionalised optical plastic film, or a combination thereof. According to a particular aspect, any one of the plurality of the

optical plastic films may comprise a combination of two one-sided surface functionalised optical plastic films arranged in series. For example, at least one of the plurality of the optical plastic films may comprise a series of two optical plastic films arranged in series. In particular, the at least one of the plurality of the optical plastic
5 films may comprise a series of a one-sided diffuse surface optical plastic film and a one-sided grating surface optical plastic film.

Even more in particular, the optical panel may provide transmission of the visible light of different intensities across the spectrum of wavelength of the visible light based on the functional surface comprised on the plurality of optical plastic films. In this way, the
10 optical panel may negate the use of electronic counterparts such as LED drivers and micro-controllers. For example, the optical panel may block or partially block the incident polarized or partially polarized light. Accordingly, when used in an indoor farm, the optical panel enable the farm to be lit, but use of the optical panel may enable the plants not to receive light.

15 The method may also be used in buildings where it is required for the optical panels and/or optical plastic films to control the amount of light entering indoors.

The method of the present invention is an electricity-free method of controlling the intensity of light, thereby consuming less energy and being environmentally friendly. Further, the method is not affected by indoor climate, humidity, temperature or other
20 factors, thereby allowing the method to be used in across multiple applications and in different locations without having to make too many changes to the method.

Having now generally described the invention, the same will be more readily understood through reference to the following example which is provided by way of illustration, and is not intended to be limiting.

25 **Example**

A 5 μm grating patterned photoresist master template was prepared via photolithography. Firstly, the photomask was cleaned by soaking in AZ stripper AZ300T overnight to remove any resist residuals. A Si substrate was treated with hexamethyldisilazane (HMDS) and spin coated using photoresist at a speed of 5000
30 rpm for 45 s and prebaked at a temperature of 105°C for 90 s and followed by 60 min

of rehydration. This was then followed by UV exposure at an energy dose of 300 mJ/cm² for 11 s using mask aligner and developed using AZ400K and deionized water at a ratio of 1:3 for 45 s.

5 The patterned photoresist of 5 μm grating master template acts as a sacrificial layer where it dissolves in solvent after the electroforming and leaves a clean nickel surface with good yield. Nickel vanadium (NiV) alloy was deposited on the resist template as a conductive seed layer. This was then followed by electroforming of the master template using Ni electroplating system. The NiV coated resist template was electroplated at a plating current density of 2.5 Å/dm² to form a Ni master to a thickness of 230 μm. After
10 the plating process, the Si substrate could easily detach from the Ni replicate. The residue of patterned resist layers stuck to the Ni surface. To strip off these layers, the Ni mold was rinsed with acetone and IPA, followed by O₂ reactive ion etching (RIE) plasma cleaning at 80 sccm with a radio-frequency (RF) power of 100 W at a process pressure of 30 mT for duration of 2 min. The mold was then washed with deionized
15 water and blew dry with nitrogen gas. Finally, the Ni mold was laser trimmed to the required dimension using a UV laser. The Ni mold had an active area (overall area) of about 3.5 cm x 3.5 cm.

The Ni mold with grating structures had a grating width of about 5 μm, gap of about 4 μm, height of about 5 μm.

20 The other Ni mold employed imparted diffuse surface upon imprinting, had a roughened surface and offered a matt-like finish on the imprinted film.

Ni molds with pyramids and inverse pyramid structures were also used to fabricate imprints on a polycarbonate (PC) film. The sides of the pyramids measured 750 nm with a spacing of about 100 nm. The imprinted PC samples were then studied for their
25 optical behaviour. Prior to imprinting, all molds were vapor deposited with perfluorodecyltrichlorosilane that facilitated easy demolding. The size of the imprinted gratings on PC was 7 cm x 7 cm with an active area of 12.25 cm² at the center. The size of the imprinted diffuser sample was 10.5 cm x 10.5 cm with an active area of 63.59 cm² at the center. The mold with pyramid and inverse pyramid structures had an
30 active area of about 2 cm x 2 cm.

The PC was imprinted using the nickel mold with gratings structure at 180°C, 40 bar for 600 s using a 6" nanoimprinter. The conditions were the same for imprinting the diffuse surface as well. Upon nanoimprinting lithography (NIL), the resulting pattern characteristics on the imprinted PC, specifically, the feature heights, width, and periodicity were characterized using a confocal laser scanning microscope. The optical studies on percentage transmittance on the imprinted PC were performed using a UV-Vis spectrometer.

The Ni molds that were used to imprint PC sheets are shown in Figure 1. Figure 1A shows the mold with gratings, while Figure 1B shows the top view of the mold that imparts diffuse surface on the PC sheet. The molds were used to imprint on one side of the PC to transfer the patterns on the mold to PC, as shown in Figure 2A and 2C. A simultaneous two-side thermal imprinting using a Ni mold with gratings on one side of the PC and another that imparts diffuse surface on the other side of the bestowed PC with the corresponding structured surface on its sides was also carried out to form a two-sided imprinted PC sheet, as shown in Figure 2C. The imprinted surfaces had geometries that mirrored the Ni mold.

The manner in which light interacted with a double-sided imprint consisting of grating and diffuse surfaces was different from that of two one-side imprints of gratings and diffuse surfaces arranged next to each other in a series arrangement. The schematic representation of the set-up used for the measuring the transmittance spectrum for different imprint samples is shown in Figure 3. In particular, Figures 3A and 3B shows the set up for measuring the percentage (%) transmittance of two one-sided PC sheets, one with grating structures and the other with light diffusing structures arranged in series. Figures 3C and 3D shows the set up for measuring the percentage (%) transmittance of a two-sided PC sheet with grating structures on one side and diffuse surface on other side.

The results of the % transmittance is shown in Figure 4A. Also shown in Figure 4B is the % transmittance of a polycarbonate bare film used as a control. The bare film had a % T of about 90% in the visible spectrum. PC imprinted on one side with 5 μm grating structures and the diffuse structures had % T of about 84% and 77% respectively in the visible region. Of the one-sided grating and one-sided diffuser series combination, the arrangement in which the gratings faced the light source directly had a %T of about

68% (set up of Figure 3A) while the diffuse surface facing light directly had %T of about 64% (set up of Figure 3B). With two-sided imprinted samples, the surface with gratings and the diffuse surface had a %T of about 55-60% (set up of Figure 3C) and 73% (set up of Figure 3D), respectively while facing the light source directly.

5 It can be observed in Figure 4A that the %T curves do not cross paths with each other throughout the visible wavelength range. The respective samples can be well utilized to control the intensity of the incident light to the requirement. For instance, if one needs a %T of 65-70%, the PC sample with appropriate sample arrangement can be picked up and integrated with the grow light so that the plants receive only the pre-determined
10 intensity. In this case, it's the combination of one-side grating and one-side diffuse imprints with the former facing the light source that serves the purpose.

It is observed that in the sample combination consisting of one-side grating and one-side diffusing imprints, %T is higher when the gratings face the light directly. This is because the diffuse surface is very rough and scatters incident light with ease. On the
15 other hand, the imprint with gratings do not scatter the incident light much and transmits more light comparatively.

Conversely, in the two-side imprinted samples, it is can be observed that %T is lower when the gratings face the light source than when diffuse surface faces the light. In the %T measurement of the one-side diffuse surface, light always entered the diffuse
20 surface first, passed through the interface with PC, before entering and finally exiting the PC bulk. However, with double-side imprinted samples, the configuration in which the gratings faced the light will have the light enter the PC bulk through the gratings, travel through the bulk of the PC before arriving at the interface with the diffuse structures and finally exiting. With illumination conditions remaining the same in all
25 measurements, the orientation of the diffuse surface with respect to the light source (i.e., either diffuse surface faces the incident light or away from it) strongly influenced the transmittance behaviour. The difference in optical behaviour of the different sample configurations gets translated into the respective %T performance.

The photosynthetic photon flux density (PPFD) was measured for different samples.
30 The white LED light source had PPFD of about 148 $\mu\text{Mol}/\text{m}^2/\text{S}$. The PC control sample (blank film with no patterns) and the imprints were held just beneath the light source while the detector measured the PPFD of the light passing through the imprints at a

distance of 30 cm from the light source. The PPF measured through the control PC was about 139 $\mu\text{Mol}/\text{m}^2/\text{S}$ while the gratings sample facing light source demonstrated a PPF of about 132 $\mu\text{Mol}/\text{m}^2/\text{S}$. There was no significant variation if the gratings surface faced away from the light source. The PPF measured when the diffuse surface was facing towards and against the light source was 93 and 45 $\mu\text{Mol}/\text{m}^2/\text{S}$ respectively. The sample behaviour during PPF measurements are in line with the % transmittance trend as observed in Figure 5.

Accordingly, one approach to selectively control the intensity of the incident light is to form optical panels by an array of the PC sheets. A schematic illustration of the use of the optical panels in indoor farms is shown in Figure 5. The optical panel may be installed just beneath the grow-light panel. The optical panel ensures good control over the intensity of the transmitted light that would suit the plant growth. For example, to obtain an optical panel, smaller PC imprints were stitched together. Each PC imprint was sealed to another using an impulse sealer. The sealing resulted in a sealing width of about 4 mm. Thus, there are portions on the optical panels that are structured, overlapped PC at the seal and the rest being unstructured PC.

The stitching of smaller imprints to form a bigger panel offers a quick and cheap way to fabricate optical panels. Further, this approach doesn't have a limitation on the number of smaller imprints that can be joined together. By using the same mold, several imprints may be repeatedly fabricated with excellent reproducibility without the need to clean or recoat anti-stiction layer on the mold.

Most green crops in indoor farms prefer two specific range of wavelengths of the grow-light spectrum – blue (400–500 nm) and red (600–700 nm) as the major energy source for photosynthesis. Thus, a system that allows one to control the intensity in these wavelength ranges without resorting to micro-controllers and LED drivers will significantly bring down the cost spent in lighting and control, particularly in indoor farming.

Accordingly, the incident intensity at these specific wavelength ranges may be varied by the use of optical panels made from PC sheets comprising arrays of micro-pyramid and inverse micro-pyramid structures as shown in Figure 6A and Figure 6B, respectively.

The optical responses of imprints with pyramid and inverse pyramid arrays are shown in Figure 7. The imprints with the structured side facing away from the light source transmitted lesser than the imprints facing light. The optical performance was largely guided by the geometry of the patterns and was tunable.

- 5 The % transmittance in the visible spectrum could therefore be manipulated to one's requirements by varying the geometry, such as the size, pitch and angle of the pyramid structures.

As seen above, while optical panels made from the combination of the gratings and diffuse surfaces provided a well-controlled and uniform intensity throughout the visible
10 wavelength, the panels made from pyramid and inverse pyramid structures allowed control over the intensity at different wavelengths of the visible spectrum.

Whilst the foregoing description has described exemplary embodiments, it will be understood by those skilled in the technology concerned that many variations may be
15 made without departing from the present invention.

Claims

1. A method of controlling intensity of visible light, the method comprising: passing visible light through an optical plastic film, the optical plastic film comprising at least one functional surface that interacts with incident visible light to control the intensity of the incident visible light by transmitting 50-90% of the incident visible light without the use of electricity.
2. The method according to claim 1, wherein the optical plastic film is provided on an optical panel.
3. The method according to claim 2, wherein the optical panel comprises a plurality of the optical plastic films, each of the plurality of the optical plastic films comprising the same or different functional surface from the other.
4. The method according to claim 3, wherein the optical panel provides transmission of the visible light of different intensities across the spectrum of wavelength of the visible light based on the functional surface comprised on each of the plurality of optical plastic films.
5. The method according to any preceding claim, wherein the at least one functional surface is formed on the at least one optical plastic film by nanoimprint lithography.
6. The method according to any preceding claim, wherein the at least one functional surface comprises a diffuse surface, grating surface, three-dimensional patterning, or a combination thereof.
7. The method according to claim 6, wherein the grating surface comprises grating structures having a pre-determined grating width, gap and height.
8. The method according to claim 7, wherein the pre-determined grating width is 3-8 μm .

9. The method according to claim 7 or 8, wherein the pre-determined gap is 3-7 μm .

10. The method according to any of claims 7 to 9, wherein the pre-determined
5 height is 3-8 μm .

11. The method according to claim 6, wherein the three-dimensional patterning comprises pyramid structures, inverse pyramid structures, or a combination thereof.

10 12. The method according to any preceding claim, wherein the optical plastic film comprises two functional surfaces.

13. The method according to claim 12, wherein the two functional surfaces of the optical plastic film comprise a diffuse surface and a grating surface, respectively.

15

14. The method according to any preceding claim, wherein the optical plastic film is formed from polycarbonate.

15. The method according to any preceding claim, wherein the method enables a
20 pre-determined wavelength of the visible light to be transmitted through the optical plastic film.

Figure 1A

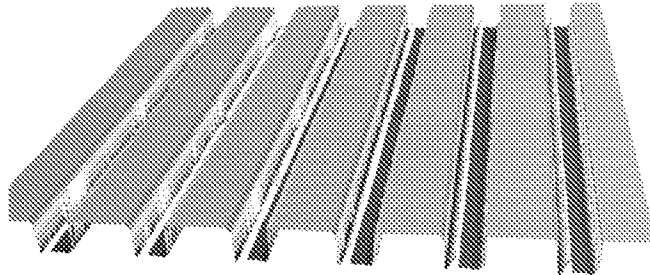


Figure 1B

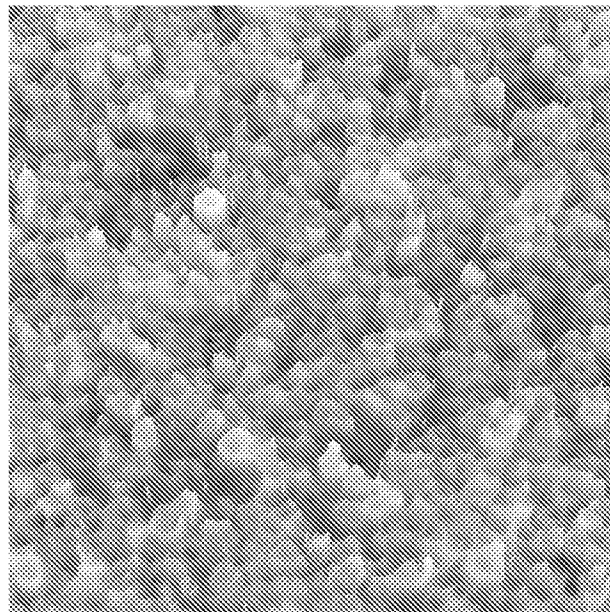


Figure 2A

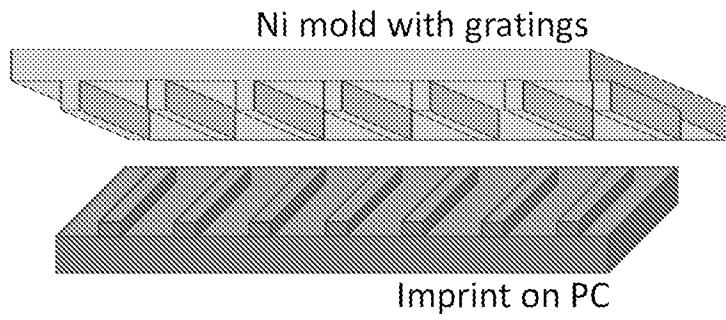


Figure 2B

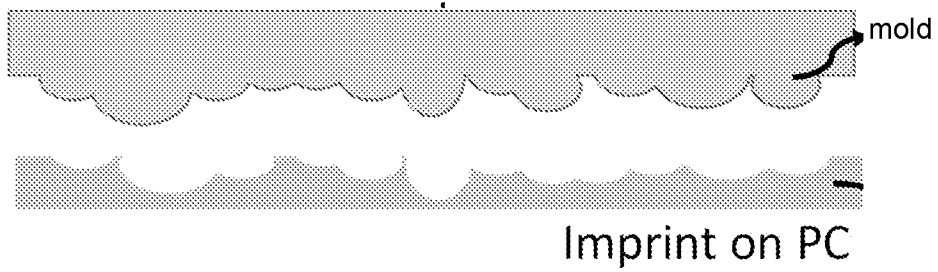


Figure 2C

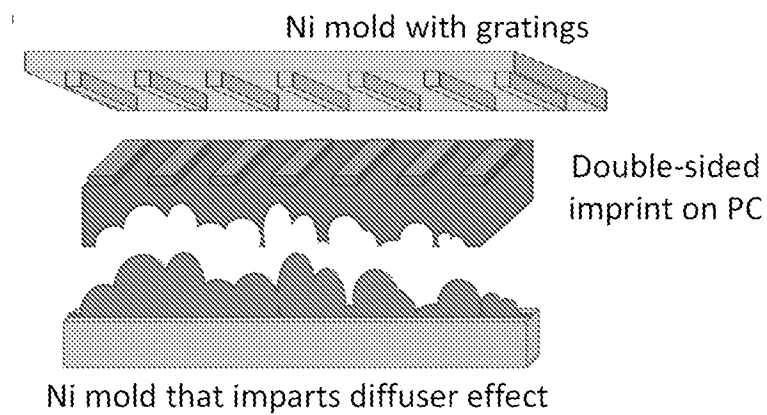


Figure 3

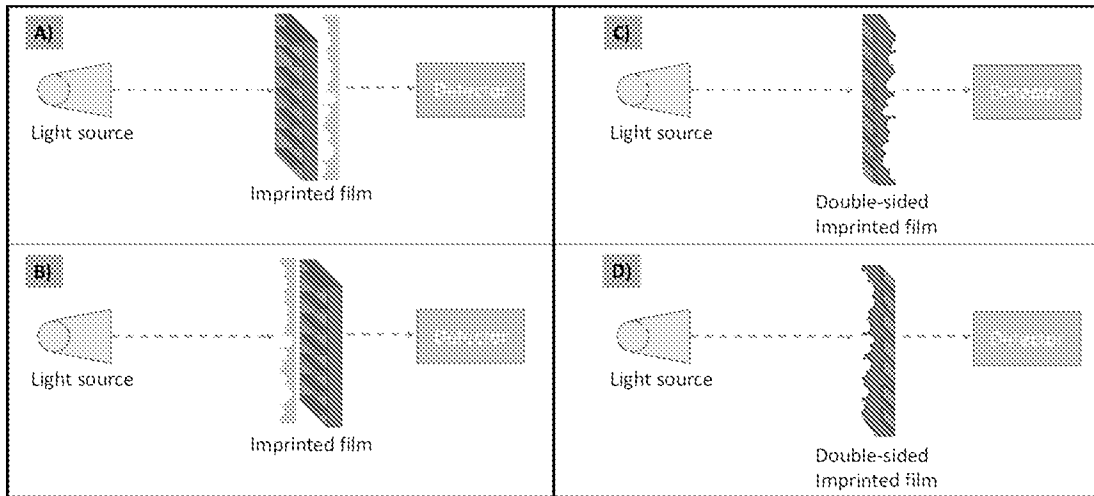


Figure 4A

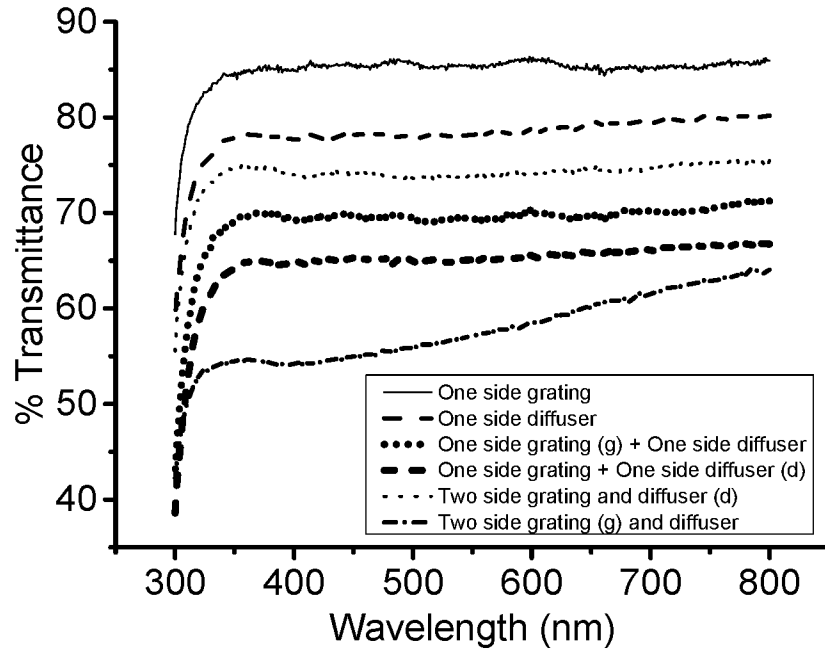


Figure 4B

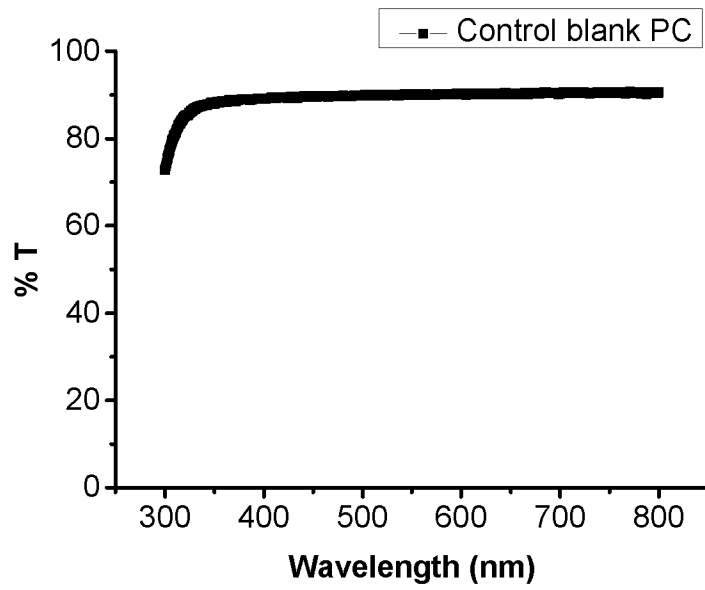
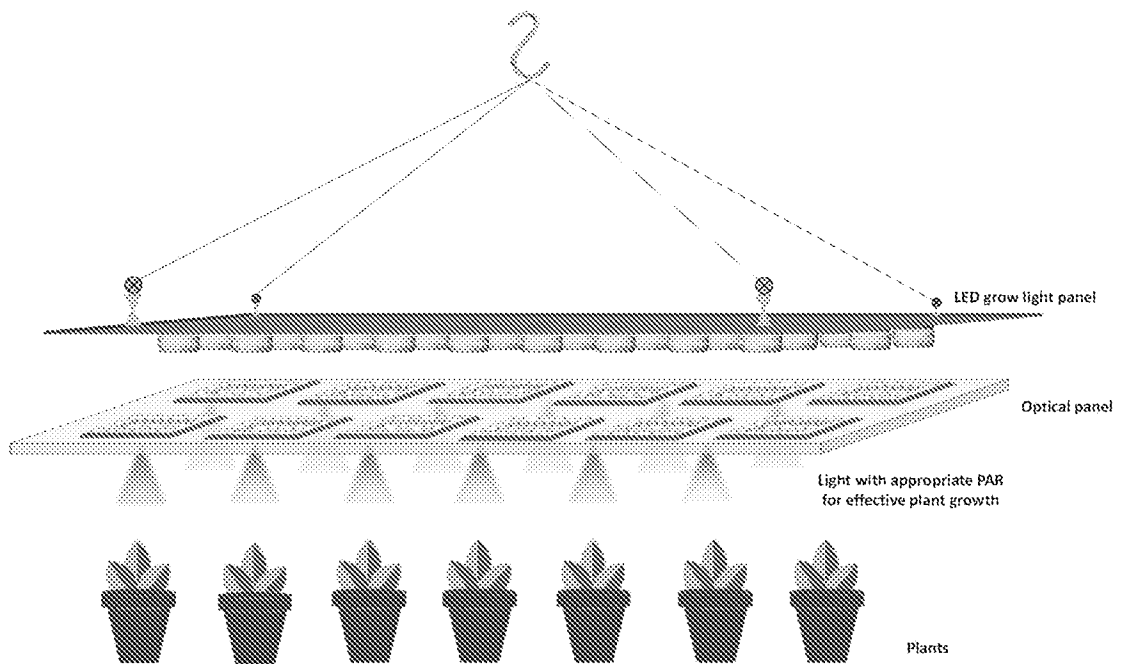


Figure 5



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Figure 6A

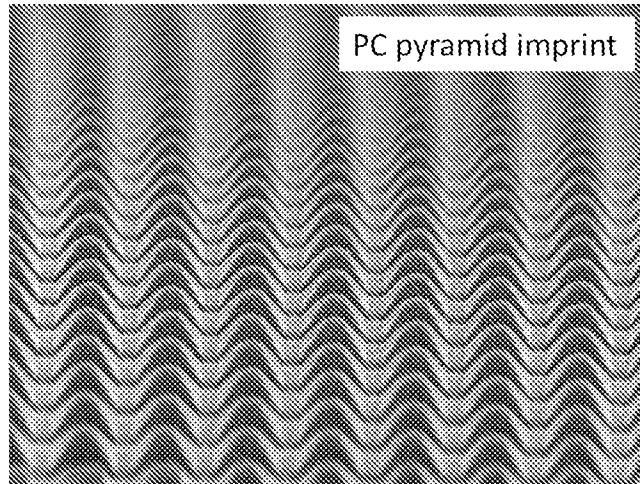


Figure 6B

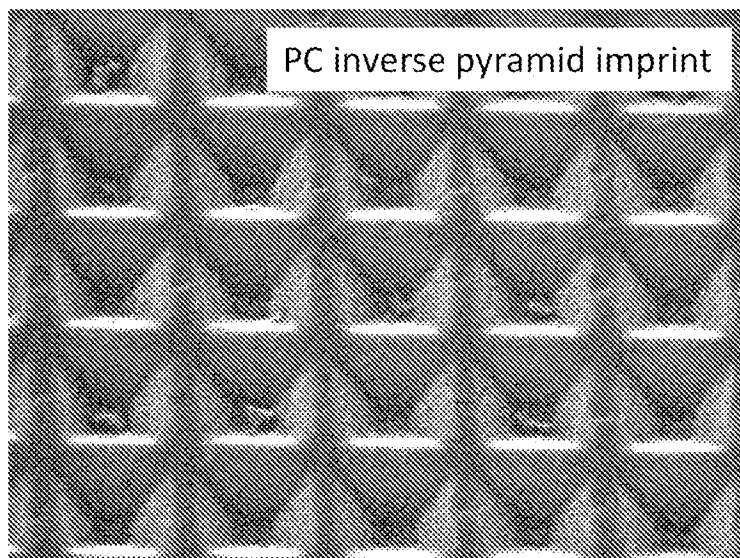


Figure 7

